THE UNIVERSITY OF CALGARY

Biomechanical Factors Associated With Patellofemoral Pain Syndrome in Runners

by

Prothromo Stergiou

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF MEDICAL SCIENCES

CALGARY, ALBERTA

JANUARY, 1996

THE UNIVERSITY OF CALGARY

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Biomechanical Factors Associated With Patellofemoral Pain Syndrome in Runners" submitted by Prothromo Stergiou in partial fulfilment of the requirements for the degree of Master of Science.

Supervisor, Dr. B.M. Nigg
Department of Medical Sciences

Dr. M. Hawes
Faculty of Kinesiology

Dr. P. Wiley
Department of Medical Sciences

Dr. J. Ronsky
Department of Mechanical Engineering

January 18, 1996

Abstract

This study was aimed at examining functional variables that were hypothesized to be related to the onset of Patellofemoral Pain Syndrome (PFPS) in runners. These variables included maximal tibial rotation with respect to the foot ($\Delta\rho_{max}$), maximal tibial rotation with respect to the femur ($\Delta\psi_{max}$), maximal patellofemoral joint contact force (F_{PFmax}), Quadriceps-angle (Q-angle), and weekly training distance. Three groups of runners participated in a 3-dimensional kinematic and kinetic evaluation of their running styles. These groups included an asymptomatic group, a group experiencing PFPS and a group who had experienced PFPS in the past with no pain at the time of the study. The third group was added to the study to control for any changes in biomechanics which may be due to pain.

The analysis was divided into a group comparison and a comparison of individual results. Group comparisons performed using a multivariate ANOVA revealed that no variables were different across the groups ($\alpha = 0.05$). A Discriminant Function Analysis revealed maximal tibial rotation with respect to the femur (ψ_{max}) was the only variable to have predictive capabilities, properly classifying 54.7 % of all cases. Since PFPS is a multifactorial problem, individual subject results were able to show which variables may have been responsible for the onset of PFPS. The most frequent combination of factors for people with PFPS was a high Q-angle and a high maximal tibial roation with respect to the femur.

Acknowledgements

I would like to express my sincerest appreciation to the following people:

Dr. Benno Nigg, my supervisor, for the direction, guidance and opportunity he has provided me with.

Dr. Preston Wiley and Dr. Mike Hawes for being on my committee and providing me with constructive critisisms.

Katherine Ladley, Nancy Gocal and the secretarial staff at the University of Calgary Sports Medicine Centre for helping with my medical record search that I thought would never end.

Dr. Janet Ronsky for the guidance and expertise she provided me when I was preparing my grant proposal.

Glenda McNeil and Byron Tory for their computer expertise during my data collection.

Dr. Tak Fung for his help and patience during our numerous statistical consultations.

Andrew Tavender and Linda Kechkes for their help in data collection and data analysis.

Stelios Komianos for his help with data collection and preparation of this Thesis.

Gerald Cole, Gordon Hamilton, Darren Stefanyshyn and Christoph Reinschmidt, my fellow graduate students, for their constuctive criticisms and comical relief during my stay.

The Canadian Lifestyle and Research Institute for providing me with financial support for this study.

To my parents, sister, brother-in-law and nephew for the understanding, love and support they have provided throughout my life.

To all my friends in Calgary that made my stay an unforgettable experience.

Dedication

In Memory of my best friend and first love,

Karla Shizuye Kitamura

September 2, 1969 - June 22, 1995

Table of Contents

Approval Page. ii
Abstract. iii
Acknowlegements. iv
Dedication. vi
Table of Contents. vii
List of Tables. ix
List of Figures. xi

1. Introduction 1

2. Review of Literature 8
2.1 Patellofemoral Pain Syndrome(PFPS) 8
2.1.1 Definition 8
2.1.2 Anatomy of the Patellofemoral Joint 10
2.1.3 Patellar Motion 13
2.1.4 Patellofemoral Joint Kinetics 18
2.1.5 Treatment of Patellofemoral Problems 22
2.2 Epidemiology of Running Injuries 25
2.2.1 Running Injury Statistics 25
2.2.2 Factors Associated With PFPS 28
2.2.2.1 Movement 29
2.2.2.2 Anatomy 35
2.2.2.3 Training 38
2.3 Summary 40

3. Methods 42
3.1 Subject Selection 42
3.2 Selection of Variables 44
3.3 Data Collection 47
3.3.1 Anthropometric Measurements 47
3.3.2 Kinematic and Kinetic Measurements 47
3.4 Data Analysis 51
3.4.1 Kinetic and Kinematic Data 51
3.4.2 Maximal Patellofemoral Joint Contact Force (F_{PFmax}) 54
3.4.3 Statistical Analyses 64
3.4.3.1 Reliability Measurements 64
3.4.3.2 Analysis of Variance 64
3.4.3.3 Stepwise Discriminant Analysis 65

3.4.4 Data Interpretation 65
3.4.4.1 Group Analysis 65
3.4.4.2 Individual Subject Analysis 67

4. Results 68
4.1 Subject Demographics 68
4.2 Reliability Measurements 69
4.3 Analysis of Variance 69
4.3.1 Maximal Tibial Rotation with Respect to the Foot ($\Delta\rho_{max}$) . . 71
4.3.2 Maximal Tibial Rotation With Respect to the Femur ($\Delta\psi_{max}$) . 71
4.3.3 Maximal Patellofemoral Joint Contact Force (F_{PFmax}) 72
4.3.4 Quadriceps-angle (Q-angle) 73
4.4 Discriminant Function Analysis 74
4.5 Training Variables 74
4.6 Individual Subject Differences 76

5. Discussion 79
5.1 Group Differences 79
5.2 Individual Subject Differences 87

6. Conclusions 90

References 94

Appendix 103

List of Tables

Table 2.1: Summary of Literature Related to Movement of the Knee Joint and Corresponding Movement of the Patella 18

Table 2.2: A Summary of Knee Injuries in Jogging Presented as a Percentage of Total Injuries and Taken From Sources Which Included Sports Medicine Clinics, Road Races, Commercial Studies and Educational Institutions (adapted from Bahlsen,1988)....27

Table 2.3: Training Variables Related to Running Injuries From Four Epidemiological Studies with Sample Sizes Greater Than 450 Subjects....39

Table 3.1: Possible Mechanisms and Mechanical Reasons for Five Functional Variables Associated With Patellofemoral Pain Syndrome in Runners....45

Table 3.2: Variable Comparisons of Maximal Ankle Moment, Maximal Knee Moment and Maximal Knee Flexion Angle to Past Studies (*** represents data not available)....62

Table 4.1: Subject Data for Five Variables Comparing Across Three Groups (mean $\pm$ S.E.)....68

Table 4.2: Reliability Measurements Using Chronbach's Alpha Coefficient (α_{chron})....69

Table 4.3: Group Comparisons for Dynamic Anthropometric and Training Variables (mean $\pm$ S.E., with the number of subjects/variable presented in parentheses) 70

Table 4.4: Comparison of Asymptomatic Values to Other Studies..................70

Table 4.5: Training Related Variables Comparing Across Groups (mean ± S.E.)..........75

Table A1: Individual Subject Data for the **Asymptomatic Group**. Averages are Presented for Three Trials for all Variables Except for Q-ang, and Weekly Running Distance Where Only One Trial is Presented........102

Table A2: Individual Data for the **PFPS Group**. Averages are Presented for Three Trials for all Variables Except for Q-ang, and Weekly Running Distance Where only one Trial is Presented 103

Table A3: Individual Data for the **Past-PFPS Group**. Averages are Presented for Three Trials for all Variables Except for Q-ang, and Weekly Running Distance where only one Trial is Presented...............................104

Table A4: Individual Subject Differences for the **Asymptomatic Group** Presented as the Percentage Difference from the Average of the Asymptomatic Group...105

Table A5: Individual Subject Differences for the **PFPS Group** Presented as the Percentage Difference from the Average of the Asymptomatic Group...106

Table A6: Individual Subject Differences for the **Past-PFPS Group** Presented as the Percentage from the Average of the Asymptomatic Group 107

List of Figures

Figure 2.1: Classification of Patellofemoral Pain Syndrome into Categories and Sub-categories (adapted from Merchant, 1988)..............................9

Figure 2.2: The Patellofemoral Joint and the Quadriceps Mechanism (Javadpour et al., 1991)...10

Figure 2.3: Posterior View of the Articulating Surfaces of the Patella Showing the Medial, Lateral and Odd Facets 11

Figure 2.4: Patellar Kinematics Showing Medial Shift, Flexion, Medial Tilt and Medial Rotation (adapted from van Kampen and Huiskes, 1990).......12

Figure 2.5: Initial Ground Contact During Heel-Toe Running Showing Supinated Foot Followed by Full Pronation of the Foot at Midstance (Left Foot) (adapted from Nike, 1989)...29

Figure 2.6: Foot Eversion and Internal Tibial Rotation for Stance Phase of Heel-Toe Running (mean $\pm$ S.E. plotted) (from Nigg et al., 1993)..........30

Figure 2.7: Support Moment Shown as the Sum of All Moments at the Hip, Knee and Ankle Joints (from Winter, 1980).......................................32

Figure 2.8: Quadriceps Angle (Q-angle) Measurement for Right Leg Using Location Points of Anterior Superior Iliac Spine (ASIS), Centre of the Patella (Patella) and the Insertion of the Patellar Tendon on the Tibia (Tibial Tubercle) (from Woodall and Welsh, 1990).......................36

Figure 3.1: Anterior and Lateral View of Skin Marker Locations on Left Lower Limb Including Joint Centre Markers (1 to 6) and Segment Markers (A to I) (adapted from Nigg et al.,1993).......................................48

Figure 3.2: Camera Positions in Umbrella Configuration Around Force Platform....49

Figure 3.3: Typical Curve for Heel-Toe Running Representing Tibial Rotation with Respect to the Foot (subject #1, trial #23)....53

Figure 3.4: Typical Curve for Heel-Toe Running Representing Tibial Rotation with Respect to the Femur (subject #1, trial #23)....54

Figure 3.5: Free Body Diagram of the **a)** Ankle Model and **b)** Knee Model to Predict F_{PFmax} During Heel-Toe Running (adapted, with changes, from Scott and Winter, 1990)....57

Figure 3.6: Sagittal Ankle Moment During the Stance Phase of Heel-Toe Running for a Typical Subject (subject #1, trial #23)....60

Figure 3.7: Sagittal Knee Moment During the Stance Phase of Heel-Toe Running for a Typical Subject (subject #1, trial #23)....60

Figure 3.8: Sagittal Knee Angle (Tibia with Respect to the Femur) During the Stance Phase of Heel-Toe Running for a Typical Subject (subject #1, trial #23)....61

Figure 3.9: Patellofemoral Joint Contact Force (F_{PFmax}) During the Stance Phase of Heel-Toe Running for a Typical Subject (subject #1, trial #23)....63

Figure 4.1: Maximal Tibial Rotation with Respect to the Foot ($\Delta\rho_{max}$) for Heel-Toe Running Comparing Across Three Groups....71

Figure 4.2: Maximal Tibial Rotation with Respect to the Femur ($\Delta\psi_{max}$) for Heel-Toe Running Comparing Across Three Groups....72

Figure 4.3: Maximal Patellofemoral Joint Contact Force (F_{PFmax})for Heel-Toe Running Comparing Across Three Groups....73

Figure 4.4: Quadriceps Angle Comparing Across Three Groups 73

Figure 4.5: Individual Subject Differences for the PFPS group Presented as a % Difference from the Averages of the Asymptomatic Group (Dynamic Variables) 76

Figure 4.6: Individual Subject Differences for the PFPS group Presented as a % Difference from the Average of the Asymptomatic Group (Anthropometric and Training Variables) 76

Figure 4.7: Individual Subject Differences for the Past-PFPS group Presented as a % Difference from the Average of the Asymptomatic Group (Dynamic Variables) 77

Figure 4.8: Individual Subject Differences for the Past-PFPS group Presented as a % Difference from the Asymptomatic Group (Anthropometric and Training Variables) 77

Figure 5.1: Number of Subjects (PFPS Group) for Three Variables (Q-angle, tibial rotation with respect to the foot, weekly running distance) Higher than the Average of the Asymptomatic Group 87

Figure 5.2: Number of Subjects (PFPS Group) for Three Variables (Q-angle, tibial rotation with respect to the femur, weekly running distance) Higher than the Average of the Asymptomatic Group 88

1. Introduction

In the past three decades, running has developed into a popular form of recreation and fitness. Jogging is considered one of the best forms of fitness in terms of calories burned (0.2 kcal/min/kg) (McArdle et al., 1989). It has been shown, through a review of medical charts, that running contributes to the majority of sports injuries for both a young (31.5%) and older age (40.5%) population (Matheson et al., 1993). The knee has been shown to be the most commonly injured site for runners (41.7% of total injuries) and Patellofemoral Pain Syndrome (PFPS) has been shown to be the most common injury within the injuries to the knee (25.8% of total injuries) as seen in a sports medicine clinic (Clement et al., 1981). The percentage of people in the Canadian population using running as a form of physical recreation decreased from 31% in 1981 to 18% in 1988 (Stephens and Craig, 1990). This change may be due to a switch into other physical activities or may be due to total cessation of physical activity. This second possibility has been supported by the results of a study that showed that 18% of the Canadian population has considered injury as a barrier to their ability to be physically active (Stephens and Craig, 1990). Consequently, it seems important that potential causes of running injuries are well understood in order to prevent them.

Patellofemoral Pain Syndrome (PFPS) can be defined as a disorder of the patellofemoral joint characterized by pain on the anterior aspect of the knee. The patellofemoral joint is made up by the articulations of the patella and the femur. Contact between these two bones is made throughout the stance and swing phases of running. It has been difficult for clinicians to definitively diagnose PFPS because there have been no obvious signs of pathology found using standard tests such as x-rays. However, the pain associated with this problem is indisputable. Common symptoms used to diagnose PFPS include pain under the knee cap when the knee functions under a load in flexion and pain due to prolonged sitting with the knee in a flexed position. Two clinical signs that accompany these symptoms include first, pain under the patella when it is displaced distally and pushed against the femur, and second, pain on the medial articular surface of the patella upon direct palpation (Goodfellow et al., 1976).

Proper patellar tracking from full extension to full flexion has been described as a "C" motion, looking at the patella in the frontal plane (Hungerford and Barry, 1979). When the knee is in full extension, the patella lies proximal to the trochlea. As the knee goes into flexion, the patella is drawn into the trochlea, making a firm congruent contact with the trochlea by 20^0 of flexion. The patella then moves medially, from 30 to 70^0 of flexion as it begins to sink into the intercondylar notch. From 90^0 to full flexion, the patella begins again a lateral course (Hungerford and Barry, 1979).

Patellar motion with respect to the femur has been characterized in three dimensions. During running, proper patellar motion has been documented as angular motions of flexion, medial rotation and lateral tilt and a translational motion of medial shift (McClay, 1990). Both contact areas and pressures (Hehne et al., 1982, Buff et al., 1988, Ronsky, 1994) in the patellofemoral joint do change with different knee flexion angles. Rotational motions of the lower leg with respect to the femur during running may cause the patella to change its tracking pattern within the femoral groove. This change in position of the patella with respect to the femur may cause a change in the contact area or pressure within the patellofemoral joint and may lead to excessive pressures at localized regions on the posterior surface of the patella. Several researchers have suggested that patellar malalignment associated with PFPS leads to chondromalacia (softening of articular cartilage), which may progress to severe degenerative joint disease (e.g., osteoarthritis) and pain from subchondral bone or secondary synovitis (Fulkerson and Hungerford, 1990).

Although there are many speculations regarding the association between improper patellar tracking and PFPS, the etiology of the injury is still not well understood. Speculations related to the etiology of PFPS include:

(a) Excessive motion of the foot at the subtalar joint (i.e., excessive pronation) leads to an increased internal rotation of the tibia during the stance phase of running (James et al., 1978). Since the patellar tendon is inserted into the tibia, increased rotation of the tibia may lead to an increase in excursion of the patella, changing the contact/pressure patterns in the patellofemoral joint to areas that are not usually loaded during normal daily activities. Maximal rotation of the tibia with respect to the foot ($\Delta\rho_{max}$) or with respect to the femur ($\Delta\psi_{max}$) can be looked at as variables of interest to test this speculation.

(b) Quadriceps-angle (Q-angle), defined as the acute angle between a line connecting the anterior superior iliac spine (ASIS) and the midpoint of the patella, and a line connecting the midpoint of the patella to the tibial tubercle, has been proposed as a strong discriminatory variable between runners with and without PFPS (Messier et al., 1991). A larger Q-angle may also cause a change in the contact/pressure patterns in the patellofemoral joint.

(c) Large internal joint contact forces within the patellofemoral joint (F_{PFmax}) may be one factor leading to increased stress in the joint, exceeding the physiological limits capable by the cartilage. This is speculated to lead to cartilage degeneration and ultimately subchondral bone pain.

(d) Excessive weekly training distance has been associated with running injuries and 50 to 75 % of all running injuries have been due to overuse (van Mechelen, 1992). Tissues (e.g., cartilage) within the patellofemoral joint undergo repetitive loading and may become fatigued and damaged over time.

PFPS in runners is likely a multi-factorial problem. Each subject may have different reasons for his/her PFPS. PFPS may be brought about for only one reason (e.g., high Q-angle) in some subjects and it may be brought about because of several reasons (e.g., high Q-angle and maximal tibial rotation) for other subjects. Consequently, one should not expect that the group means for the variables for subjects with PFPS to be significantly different from the group means for subjects without PFPS.

In the past, different forms of treatment have been administered to people suffering from PFPS. Two of the most common forms of treatment include physiotherapy and orthotic prescription. Quadriceps rehabilitation, focusing on strengthening of the vastus medialis, has been reported as a successful procedure leading to complete recovery from patellofemoral pain in 70% of patients (Kannus and Nittymaki, 1994). Besides exercise programs, soft foot orthotics were effective in reducing patellofemoral pain in female patients (Eng and Pierrynowski, 1993).

Many studies have focused on theoretical estimation of patellofemoral joint contact forces during various activities (Reilly and Martens, 1972, Matthews et al., 1977, Nisell and Ekholm, 1985, van Eijden et al., 1986, van Eijden et al., 1987, Buff et al., 1988, MacDonald et al., 1989, Scott and Winter, 1990, Hirokawa, 1991, Nisell and Ericson, 1992). Scott and Winter (1990) studied internal forces at sites related to chronic running injuries, including the patellofemoral joint. Results from such model calculations may provide insight into variables that cannot be measured directly through experimentation and may be used to compare non-pathological and pathological situations. However, the results of these studies could not be used to explain the etiology of PFPS.

Based on these considerations, it seems evident that answers to the potential biomechanical factors responsible for the development of PFPS may be found by studying these factors for subjects with and without PFPS. Specifically, the analysis of the Q-angle, tibio-calcaneal motion, tibio-femoral motion and patellofemoral joint contact forces for subjects with and without PFPS may provide information about the biomechanical factors responsible for the onset of PFPS. Therefore, the purposes of this study were to assess, in a retrospective study, biomechanical variables which have been proposed as being associated with the etiology of PFPS for subjects with and without PFPS. Specifically, a retrospective study was chosen to see whether or not an association existed between Q-angle, maximal tibial rotation with respect to the foot ($\Delta\rho_{max}$), maximal tibial rotation with respect to the femur ($\Delta\psi_{max}$), maximal patellofemoral joint contact force (F_{PFmax}) and PFPS.

Hypotheses tested in this study included:

a) Runners with PFPS will have a higher maximal internal rotation of their tibia with respect to the foot ($\Delta\rho_{max}$) while running.

b) Runners with PFPS will have a higher maximal internal rotation of their tibia with respect to the femur ($\Delta\psi_{max}$) while running.

c) Runners with PFPS will have a higher Q-angle.

d) Runners with PFPS will have a larger maximal patellofemoral joint contact force (F_{PFmax}) while running.

Data will be compared for the different groups with and without PFPS. Additionally, a multi-factorial analysis will be used to explore the effect of a combination of the outlined biomechanical factors to the etiology of PFPS. If these factors are found to be related to PFPS, a future prospective study may be warranted.

2. Review of Literature

2.1 Patellofemoral Pain Syndrome(PFPS)

2.1.1 Definition

Patellofemoral Pain Syndrome (PFPS) includes all disorders of the patellofemoral joint characterized by pain on the anterior aspect of the knee. Because of the location of the pain and controversy about the proper terminology, some authors have suggested that PFPS be called Anterior Knee Pain (AKP) (Jacobson and Flandry, 1989). PFPS and chondromalacia patellae have been used interchangeably in the literature to represent the same pain phenomenon. The term "chondromalacia patellae" is used in this text to describe the pathological changes to the articular cartilage within the patellofemoral joint, the term "PFPS" for the pain felt in the anterior knee. Pain does not develop into osteoarthritis, but rather physiological changes responsible for pain may develop later in life (Goodfellow et al., 1976).

Many pathologies can occur within or surrounding the patellofemoral joint. Merchant (1988) classified patellofemoral disorders using the categories and sub-categories outlined in Figure 2.1.

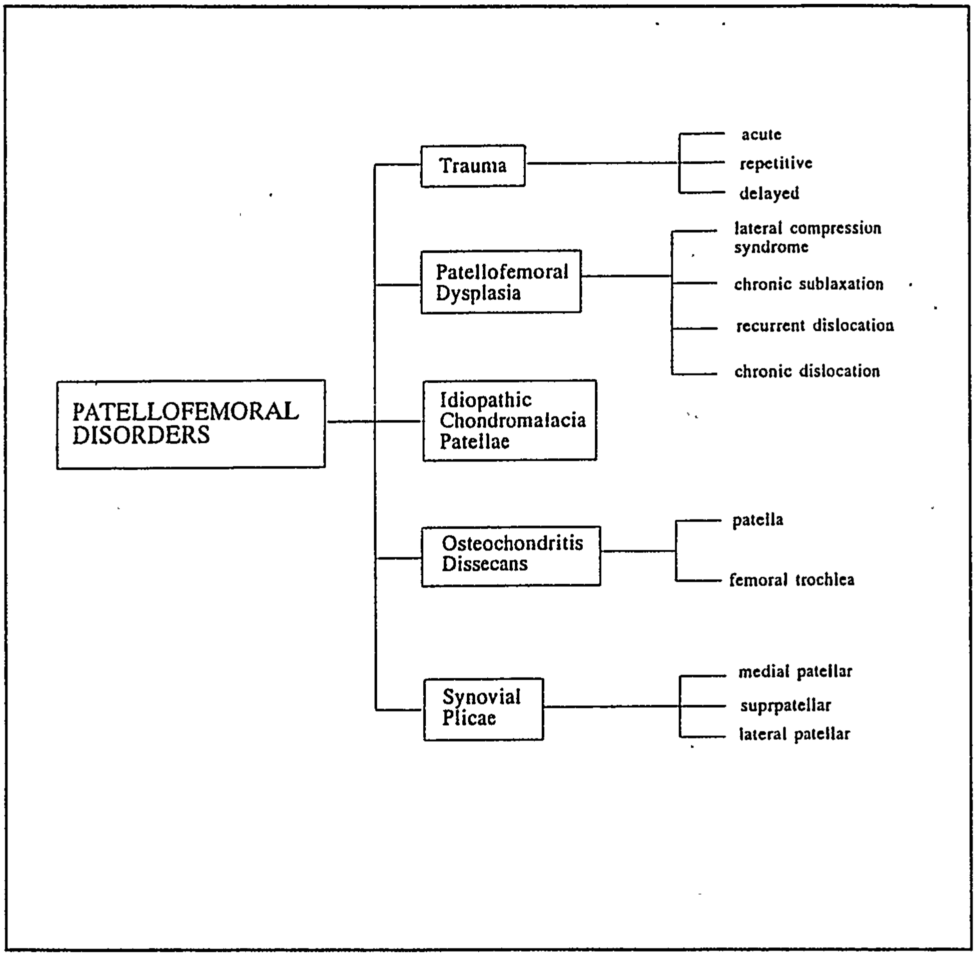

Figure 2.1:Classification of Patellofemoral Pain Syndrome into Categories and Sub-categories (adapted from Merchant, 1988)

The classification was designed for clinical use and was based on etiology. For this study PFPS was classified under category one (Trauma) and the sub-category "repetitive". The trauma, however, was not associated with patellar tendinitis, quadriceps tendinitis, peripatellar tendinitis or prepatellar bursitis.

Symptoms of PFPS include pain under the knee cap, felt when the knee functions under a load in flexion and pain due to prolonged sitting with the knee in a flexed position. Two signs that accompany these symptoms include first, retropatellar pain felt when the patella is displaced distally and pushed against the femur, and second, pain felt on the medial articular surface of the patella upon direct palpation (Goodfellow et al., 1976). Pain for runners afflicted with PFPS does not occur until well into their run (i.e., approximately 15 minutes). It has commonly been thought that pain associated with a musculoskeletal injury could change the biomechanics of a subject during testing. Any comparisons of biomechanical variables may be made difficult because differences seen may be a cause of and not causing the pain.

2.1.2 Anatomy of the Patellofemoral Joint

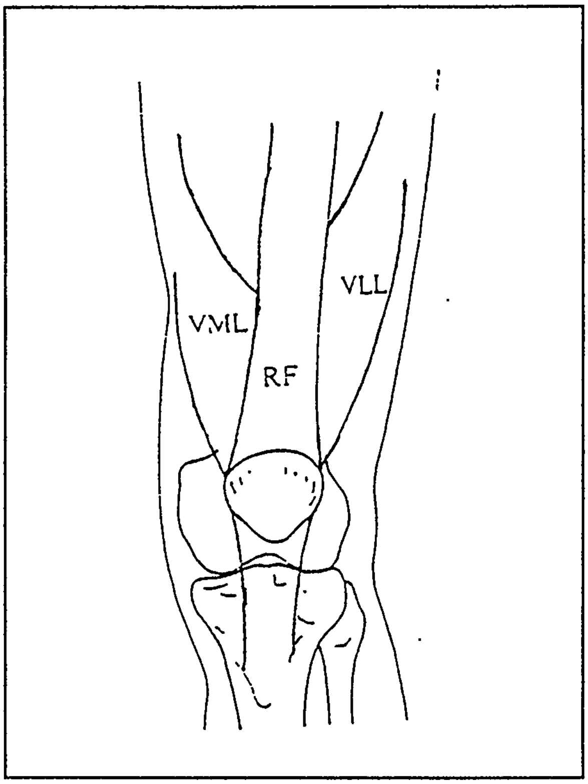

Figure 2.2: The Patellofemoral Joint and the Quadriceps Mechanism (Javadpour et al., 1991)

The knee joint complex consists of bones, muscle-tendon units, ligaments and articular cartilage. The three major bones of the knee complex are the femur, tibia and patella. The articulation between the patella and the femur is called the patellofemoral joint. The patella is a sesamoid bone embedded into the quadriceps tendon. It is triangular with the medial-lateral (width) size slightly larger than the superior-inferior (length) size and has an apex pointing distally

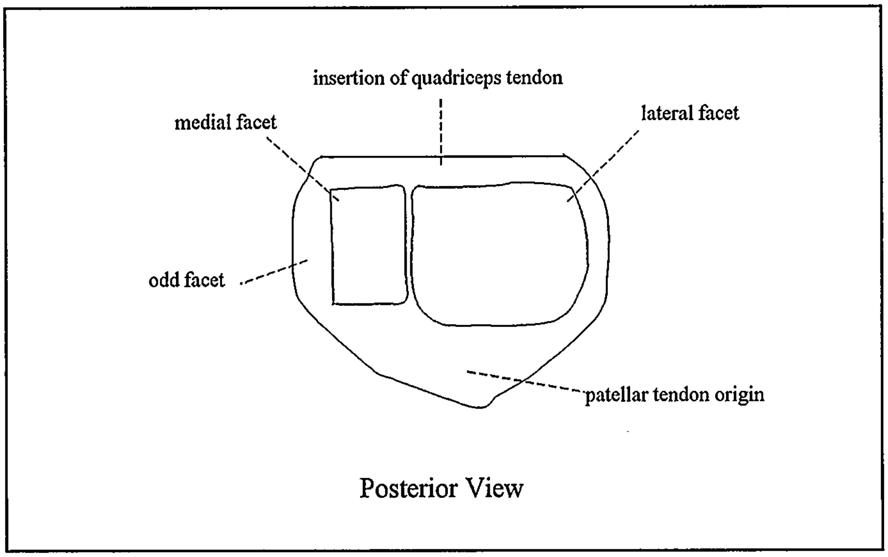

Figure 2.3 : Posterior View of the Articulating Surfaces of the Patella Showing the Medial, Lateral and Odd Facets

(Figure 2.2). The posterior portion of the patella forms the articulating surface with the femur. The inferior portion of the patella has a non-articulating surface (25% of height) and the superior portion (75% of height) articulates with the femur and is completely covered with hyaline cartilage. The articular cartilage, reaching 4-5 mm depth at the centre of the patella, is the thickest cartilage found in the human body. This articulating surface is divided into the lateral and medial facets. Both are relatively oval in shape and divided by a vertical ridge (Figure 2.3). The medial facet is further divided into the medial facet proper and a smaller odd facet separated by a vertical ridge which is smaller than that which separates the lateral and the medial facets. The shape of the odd facet is concave or flat, the medial facet proper flat or convex and the lateral facet concave (Fulkerson and Hungerford, 1990).

Hungerford and Barry (1979) state that the main function of the patella is to increase the effective lever arm of the quadriceps muscle. Secondary to this, the patella acts as a point of insertion of the quadriceps tendon for the converging quadriceps muscle

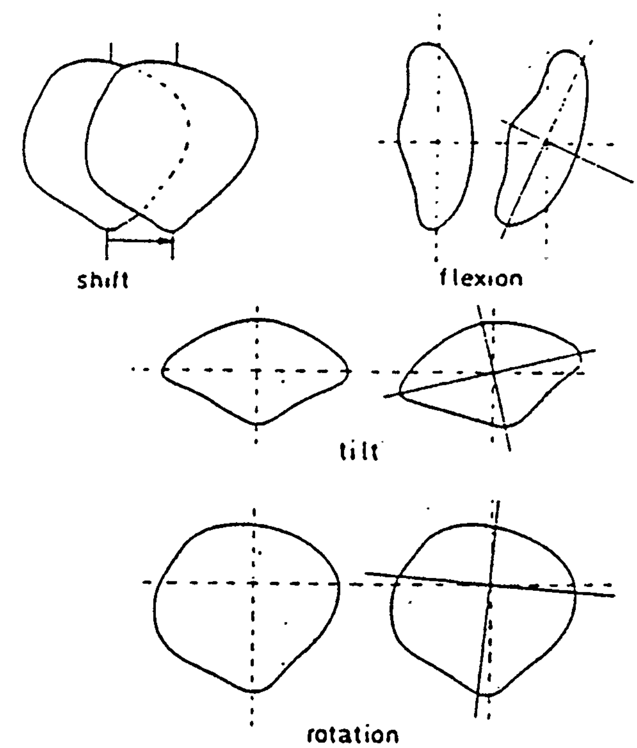

Figure 2.4: Patellar Kinematics Showing Medial Shift, Flexion, Medial Tilt and Medial Rotation (adapted from van Kampen and Huiskes, 1990)

group. The articular cartilage on the posterior surface of the patella provides an aneural and avascular tissue that is adapted to bearing high stresses. The viscoelastic nature of this cartilage allows for deformation under a load to permit contact forces to be distributed over the large area of the posterior surface of the patella.

2.1.3 Patellar Motion

Kinematics of the patellofemoral joint, both theoretical and experimental, have been studied by various investigators (van Kampen et al., 1986, Lengsfeld et al., 1990, McClay, 1990, van Kampen and Huiskes, 1990, Hefzy et al., 1992, Koh et al., 1992). The movement components of the patella have been defined by van Kampen and Huiskes (1990). Patellar motions with respect to the femur were as follows (Figure 2.4):

1. rotation about the "x" axis described patellar flexion (positive) or extension (negative)

2. rotation about the "y" axis when the medial patellar facet rotated towards the medial femoral condyle described medial tilt (positive) or when the lateral patellar facet rotated towards the lateral femoral condyle described lateral tilt (negative)

3. rotation about the "z" axis when the patellar apex turned towards the medial condyle described medial patellar rotation (positive) or when the patellar apex turned towards the lateral condyle described lateral patellar

rotation (negative)

4. translation along the femoral "x" axis was delineated as patellar shift, with positive towards the medial and negative towards the lateral

van Kampen and Huiskes (1990) used a roentgen stereophotogrammetric analysis (RSA) to determine the three-dimensional motion of the patella reconstructed based on spatial co-ordinates using markers implanted into the bones. Three Cartesian coordinate systems were applied to each of the femur, tibia and patella. The origins of these systems included: 1) the highest point of the intercondylar notch, at the cartilage border for the femur, 2) centre of the tibial plateau just behind the insertion of the anterior cruciate ligament for the tibia, and 3) centre of the patella for the patella. All three axes were parallel on extension with the "x" axes pointing medially, the "y" axes pointing superiorly and the "z" axes pointing anteriorly. The relative motions of the tibia and patella were taken with respect to the femur that was considered a space-fixed system. It was found that with knee flexion the patella underwent flexion, medial rotation and only a little medial-lateral tilt. Translational motions of the patella included a lateral shift with increased knee flexion. It was also found that an internal rotation of the tibia produced a medial tilt, a lateral rotation and medial shift of the patella.

Fresh human cadaveric whole lower limbs were used to determine the effects of tibial rotations on patellar motions for knee flexion angles between 0 and 90° (Hefzy et al., 1992). Motions of the patella relative to the femur were defined as in van Kampen and Huiskes (1990). To determine the effects of tibial rotations on the motion of the patella, the tibia was manually rotated to its maximal internal and external limits. As the knee flexed, the patella flexed for both internal and external rotation of the tibia. Internal rotation of the tibia produced significantly more medial tilt of the patella for the first 30° of knee flexion and significantly more lateral rotation in the last 30°. Also, it was found that internal tibial rotations caused a significant increase in medial shift of the patella during the first 30° of knee flexion.

Using bone pins implanted into the tibia, femur and patella of one human subject, Koh and co-workers (1992) documented the motion of the patella during seated and squatted flexion-extension. Using the same coordinate system as the above mentioned study by van Kampen and Huiskes (1990), it was found that during seated flexion-extension the patella underwent flexion, tilted laterally and showed very little medial-lateral rotation. The patella also underwent lateral shift with knee flexion. Similar results were seen for the squatted flexion-extension movement. This data, at least qualitatively, agreed with the van Kampen and Huiskes data. Koh and co-workers (1992) agreed that van Kampen and Huiskes (1990) were successful in reproducing *in vivo* patellar tracking using cadaveric specimens. Some quantitative differences seen may reflect the intersubject differences in the bony and ligamentous constraints to patellar motion.

Motion of the patella has also been documented during actual running (McClay, 1990). Four male recreational runners had intracortical bone pins inserted into the tibia, femur and the patella. Two of the subjects had a history of patellofemoral pain and the other two were asymptomatics. Tibial, femoral and patellar rotations and translations were documented for treadmill running at 3.35 m/s. All motions were described with respect to an anatomical coordinate system. The motions discussed in this text were defined as follows:

1. **Tibiofemoral Internal Rotation:** a rotation of the tibia about its longitudinal axis resulting in the tibial tubercle rotating towards the midline of the body

2. **Tibiofemoral Adduction:** a rotation of the tibia about the anterior-posterior axis resulting in the distal tibia being brought in towards the midline of the body

3. **Patellofemoral Abduction:** a rotation of the patella about the anterior-posterior axis in a clockwise direction for the right leg and in a counterclockwise direction for the left leg

4. **Patellofemoral Medial Translation:** a translation of the patella medially of the origin of the patellar anatomical system with respect to the femoral anatomical system along the fixed femoral (mediolateral) axis

In general, both groups displayed tibiofemoral internal rotation and adduction with tibiofemoral flexion. As the knee flexed, there was a general trend of the patella to abduct, and translate medially. This is opposite to what both van Kampen and Huiskes (1990) and Koh and co-workers (1992) found. However, as the knee flexes during running, it is coupled with an internal rotation of the tibia with respect to the femur. Since the patellar tendon is inserted into the tibial tuberosity, an internal rotation of the tibia may produce medial shift of the patella. Furthermore, this running study (McClay, 1990) revealed that the PFPS subjects showed the maximal internal rotation of the tibia with respect to the femur 25 ms later than the asymptomatic subjects and that the PFPS subjects exhibited 2.75 times the mediolateral excursion of the patella. This difference may play a role in the pathology of the PFPS subjects, but there was no speculation about how the pathology may occur. Since there were only two subjects per group, and considering the large intersubject variability, no statistical conclusions were made from this data.

The movement of the patella relative to the femur can be summarized in Table 2.1 as follows:

Table 2.1: Summary of Literature Related to Movement of the Knee Joint and Corresponding Movement of the Patella

MOVEMENT OF THE KNEE JOINT	MOVEMENT OF THE PATELLA
• knee flexion (*in vitro*) (van Kampen and Huiskes, 1990)	• flexion, medial rotation, minimal tilt, lateral shift
• knee flexion and maximal range internal tibial rotation (*in vitro*) (Hefzy et al., 1992)	• flexion, medial tilt (between 0 to 20° of knee flexion), lateral tilt (20 to 90°), minimal rotation (0 to 40°), medial rotation (40 to 90°), minimal shift
• knee flexion and maximal range external tibial rotation (*in vitro*) (Hefzy et al., 1992)	• flexion, medial tilt (0 to 40°), lateral tilt (40 to 90°), minimal rotation (0 to 40°), lateral rotation (40 to 90°), minimal shift
• seated knee flexion (*in vivo*) (Koh et al., 1992)	• flexion, lateral tilt, minimal rotation, lateral shift
• squatted knee flexion (*in vivo*) (Koh et al., 1992)	• flexion, lateral tilt, minimal rotation, lateral shift
• knee flexion "running" (*in vivo*) (McClay, 1990)	• flexion, minimal tilt, medial rotation, medial shift

2.1.4 Patellofemoral Joint Kinetics

Many studies quantified the contact areas, forces and/or pressures within the patellofemoral joint (Reilly and Martens, 1972, Matthews et al., 1977, Townsend et al., 1977, Huberti and Hayes, 1984, Nisell and Ekholm, 1985, van Eijden et al., 1986, Buff et al., 1988, Macdonald et al., 1989, Scott and Winter, 1990, Hirokawa, 1991, Hefzy et al., 1992, Nisell and Ericson, 1992, Lee et al., 1994, Ronsky, 1994).

In an experiment using a whole cadaveric limb, Hefzy and co-workers (1992) tested the effect of tibial rotations on the contact area of the patellofemoral joint. It was found that at knee joint angles between 0 to 90°, the magnitude of the total contact area of the patellofemoral joint did not change significantly as the tibia was manually manipulated from end range internal to end range external tibial rotation. However, the medial and lateral components of the contact area did shift as the tibia was rotated. Medial patellar contact areas increased with internal rotation and lateral contact areas increased with external tibial rotation.

Ronsky (1994) studied *in-vivo* patellofemoral joint contact in five human subjects with unilateral anterior cruciate ligament (ACL) deficiency. Testing both limbs separately, magnetic resonance imaging was used to determine the detailed geometry of the articulating surfaces under isometric loading conditions of the quadriceps muscles. The region of contact between the patella and the femur was modelled using an analytical technique. The surfaces of the patella and the femur were reconstructed using a surface reconstruction algorithm. The subjects were tested at three different knee flexion angles (15, 30 and 45^0). The results showed that patellofemoral joint contact increased with increasing knee flexion angle for the intact ACL leg (0.56 ± 0.32 cm^2 at 15^0 to 2.05 ± 0.62 cm^2 at 45^0 flexion). However, the contralateral ACL-deficient knees showed no consistent trend for increasing contact area with increased knee flexion angle. As the knee was placed in a more flexed position, the contact area moved more proximally for the ACL-intact limb. Two of the ACL-deficient knees had a pronounced reduction of migration of the contact area with increased knee flexion angle, while the other three ACL-deficient knees showed similar patterns as seen for the ACL-intact knees.

Scott and Winter (1990) studied forces within joints at sites commonly associated with running injuries. A two-dimensional model of the patellofemoral joint in the sagittal plane was used to determine the patellofemoral joint contact force. The model predicted a maximal patellofemoral compressive joint force of 3750 N occurring at approximately 40% of stance. This corresponded to 7.6 times body weight and occurred concurrently with maximal knee flexion. Based on the results of the study by Scott and Winter (1990), it can be speculated that this large internal force during running may be a factor that may contribute to the susceptibility of this joint to injury.

In another study, forces in the patellofemoral joint were determined using eight cadaveric lower limbs (Buff et al., 1988). Using a simple two dimensional model, the patellofemoral joint reaction force presented a maximum at 60° flexion decreasing to 31% of maximal force at full extension. Macdonald and co-workers (1989) studied patellofemoral contact forces in patients with anterior knee pain or chondromalacia patellae and in asymptomatic subjects. Isometric knee extensions were measured in 18 subjects at knee flexion angles between 30 and 90°. A two dimensional sagittal plane model estimated the patellofemoral joint contact force. It was found that patients with combined anterior knee pain and chondromalacia patellae had significantly lower patellofemoral contact forces at all angles of knee flexion, except at 30°, compared to the asymptomatic group. The group that had anterior knee pain but no chondromalacia showed no difference in contact forces from the asymptomatic group. The design of the study did not allow to conclude whether the decrease observed in the chondormalacia patients was the cause or the effect of the injury.

Contact areas, forces and pressures on the patellofemoral joint have been quantified theoretically and experimentally. A migration of contact areas within the patellofemoral joint with changes in tibio-femoral position has been reported in both *in vitro* (Hefzy et al., 1992) and *in vivo* (Ronsky, 1994) studies. Forces in the patellofemoral joint change with varying knee flexion angles (Buff et al., 1988) and in subjects with chondromalacia patellae (Macdonald et al., 1989). To the author's knowledge, no studies have been done comparing forces during actual running for subjects with and without patellofemoral pain. The studies presented above do show that the change in contact area occurs, however, the theoretical force calculations are difficult to compare quantitatively because the methods used in calculations are different. It is not clear in the literature how these forces or changes in contact areas may be related to patellofemoral joint problems in runners. No studies have been found estimating patellofemoral joint contact forces between runners with and without PFPS during actual running.

2.1.5 Treatment of Patellofemoral Problems

Many rehabilitation protocols have been presented in the literature for patellofemoral joint problems (Callaghan and Balzopoulos, 1992, Gaffney et al., 1992, Zappala et al., 1992, Eng and Pierrynowski, 1993, Finestone et al., 1993, Steinkamp et al., 1993, Kannus and Niittymaki, 1994) to reduce pain and improve function through exercise, rest and/or mechanical devices.

In a review of literature related to anterior knee pain, Callaghan and Balztopoulos (1992) stated that the treatments associated with rehabilitating the patellofemoral joint have been conservative and the rationale has been largely empirical. Most assessments of patients with anterior knee pain have been made using subjective measurements (e.g., pain). Many studies conducted in the area of anterior knee pain have taken theoretical perspectives. However, the tools are now available to perform gait analysis to a point where meaningful kinetics and kinematics could be used to help people with anterior knee pain.

Exercise protocols have been evaluated for the treatment of patellofemoral pain (Steinkamp et al., 1993). One protocol included a leg extension exercise and the other included a leg press exercise. A simple two-dimensional model in the sagittal plane was used to calculate the variables of knee moment, patellofemoral joint reaction force and patellofemoral joint stress. The results showed that all three variables were significantly larger for the leg extension exercise at angles of 0 to 30° of knee flexion and significantly smaller for angles of 60 to 90° of knee flexion. The ramifications of this study suggest that people with patellofemoral joint problems may tolerate the leg press exercise better because it represents lower patellofemoral joint stresses within the functional range of motion. The calculation of these stresses on the patellofemoral joint was only considered in the sagittal plane, however, movement out of this plane is evident for daily locomotion. Contact areas used in this study did not consider motion in the transverse plane. Rotational movement about the long axis of the lower leg may cause a movement of the patella out of the sagittal plane, thus changing the contact area and ultimately the joint stress.

Kannus and Niittymaki (1994) found that 70% of their patients, after a period of six months, experienced complete recovery after treatment with rest, nonsteroidal anti-inflammatory drugs (NSAID's) and intense isometric quadriceps exercises. The only variable that was significantly correlated to improvements in the Visual Analog Scale (VAS) for pain and the Lyshholm and Tegner Scales for knee function, was age. The results showed that a young age was significantly associated (p , 0.005) with a good outcome, however, the intensity of this relationship was only moderate ($r = -0.41$).

Knee sleeves have been used to treat overuse patellofemoral pain in a group of army recruits (Finestone et al., 1993). The objective of the knee sleeve is to help maintain normal patellar tracking within the femoral groove. The treatment protocol included the use of an elastic patellar sleeve with or without a silicone patellar ring and a control group that received no treatment. After 14 weeks of treatment, the mean pain score decreased more among the recruits treated with the elastic sleeve without the patellar ring. However, there were no differences seen in pain between the sleeve and the control group. It was concluded that treatment with a patellar sleeve does not seem to be effective because the result for the no treatment group was not significantly different.

Soft foot orthotics have been used to study the effect of foot orthotics on the treatment of patellofemoral pain syndrome (Eng and Pierrynowski, 1993). Twenty female subjects participated in the study and were randomly assigned to one of two groups: a control group (n=10) which underwent an exercise program, and an orthotic group (n=10) who used soft foot orthotics besides participating in the same exercise program. Using a Visual Analogue Scale (VAS) and assessing for pain during activities such as walking, running, sitting for one hour, ascending/descending stairs and squatting, it was found that both groups demonstrated a significant decrease in the level of pain. However, the improvement of the orthotic group was significantly greater than that of the control group. It was concluded that soft foot orthotics in combination with an exercise program was effective in reducing pain in the patellofemoral joint after an 8-week program. However, no indication was given as to the pain of the subjects prior to the study commencing. The graphs presented for the VAS scores only present values for 2-8 weeks post-program. If there was an initial difference in pain, then this could lead to false conclusions about the effect of orthotics on PFPS.

In summary, exercise protocols were successful in the reduction of patellofemoral pain (Eng and Pierrynowski, 1993, Kannus and Niitymaki, 1994). Along with exercise, soft foot orthotics have been shown to further reduce patellofemoral pain (Eng and Pierrynowski, 1993). All of the above studies used subjects that had sustained PFPS via repetitive trauma, however, different activities may have been related to the onset of this PFPS, and this was not controlled for. A control for this would be to select a specific group of people (e.g., runners) for which PFPS has been shown to present a problem and only study this group. All of the studies cited above used a reactive approach to solve the problem once it had occurred and no attempts were made to find the origin of the problem. A proactive approach would attempt to find the factors associated with PFPS in order to reduce the incidence of PFPS. This proactive approach would not only help prevent injuries, but may even have larger impacts on the cost of rehabilitative health care.

2.2 Epidemiology of Running Injuries

2.2.1 Running Injury Statistics

In a 1993 study examining musculoskeletal injuries associated with physical activity, Matheson and co-workers (1993) retrospectively observed patient charts over a period of five years. Knees were reported to be the most common site of injury with the younger population (mean age = 30.4 ± 8.1 years) having a frequency of 40.7% and the older population (mean age = 56.9 ± 6.1 years) having a frequency of 29.5% of the total injuries. Running was reported to be the most common single physical activity at the time of injury with the younger population (31.5%) as with the older population (40.5%).

In a review of data on running related injuries, van Mechelen (1992) stated that the yearly incidence rate for running injuries, in studies using more than 500 subjects and a period of more than one year, varied between 37 to 56%. This incidence rate in terms of exposure of running time would equate to 2.5 to 12.1 injuries per 1000 hours of running. Bovens and co-workers (1989) reported that for a higher weekly running distance the incidence rate increased. The range reported in this study was between 7.0 to 12.1 injuries per 1000 hours of running.

Knees have been reported to be the dominant site of injury in runners (James et al., 1978, Clement et al., 1981, Walter et al., 1988). Table 2.2 summarizes various studies of the incidence/prevalence of knee injuries in jogging.

Table 2.2: A Summary of Knee Injuries in Jogging Presented as a Percentage of Total Injuries and Taken From Sources Which Included Sports Medicine Clinics, Road Races, Commercial Studies and Studies at Educational Institutions (adapted from Bahlsen, 1988)

Author(s) (year)	% of total	Source
Runner's World (1971)	18	commercial survey
Runner's World (1973)	23	commercial survey
Runner's World (1975)	25	commercial survey
James et al. (1978)	29	clinic
Clement et al. (1981)	42	clinic
Newell & Bramwell (1984)	50	clinic
Grana & Coniglione (1985)	30	clinic
Jacobs and Berson (1986)	21	road race
Marti et al. (1988)	28	road race
Walter et al. (1988)	23	road race
Bahlsen (1988)	29	prospective study
Walter et al. (1989)	27	road race

The reported frequencies of knee injuries were dependent on the location where the epidemiological data was collected. Results collected in running or sports injury clinics averaged 38%, the results collected for the prospective studies were 29%, results collected at races averaged 25% and results from commercial studies averaged 22%.

In a retrospective survey of clinical records, Clement and co-workers (1981) have shown that Patellofemoral Pain Syndrome (PFPS) was the most common injury in runners. They surveyed 1,650 patients in a sports injury clinic over a period of two years and identified 1,819 injuries, with the most common disorder in 25.8% of the patients being PFPS. Other injuries reported in this study included tibial stress syndrome (13.2%) and achilles peritendinitis (6.0%). Similarly, another study, using patients treated in a runners' injury clinic during a one year period (n=161), reported 31% of injuries to the knee to be PFPS (Grana and Coniglione, 1985).

2.2.2 Factors Associated With PFPS

Many factors have been identified by clinicians and researchers to be associated with PFPS. However, the etiology is still not well understood. Three categories related to the increased frequency of PFPS have been identified in the literature:

- Movement
- Anatomy
- Training

Excessive motion in the subtalar joint causing excessive pronation of the foot during early-mid stance and transferred to excessive internal tibial rotation, has been speculated to be a possible factor in the development of running injuries (James et al., 1978, Bahlsen, 1988, Messier and Pittala, 1988, Nike, 1989). Anatomical factors, such as arch height, have been linked with the amount of transfer of foot eversion to internal tibial rotation (Nigg et al., 1993). Training related variables such as lack of running experience and excessive weekly running distance were said to be associated with running injuries (van Mechelen, 1992).

2.2.2.1 Movement

In this text, pronation of the foot will be defined as the rotation of the foot around the subtalar joint axis that turns the plantar surface of the foot outwards (Figure 2.5). Eversion of the foot will be defined as outward rotation of the plantar surface of the foot around an anatomical axis going from the posterior to the anterior along its length. It has been proposed that foot eversion is transferred into internal tibial rotation. This coupling mechanism may be influenced by several factors such as the ankle joint ligaments (Hintermann et al., 1994) and/or the orientation of the subtalar joint axis (Sangeorzan, 1991). It is theorized that excessive internal rotation of the tibia during running may be related to the increased incidence of PFPS. Since the patellar tendon is inserted into the tibial tuberosity, excessive internal rotation of the tibia during the stance phase of running may cause the

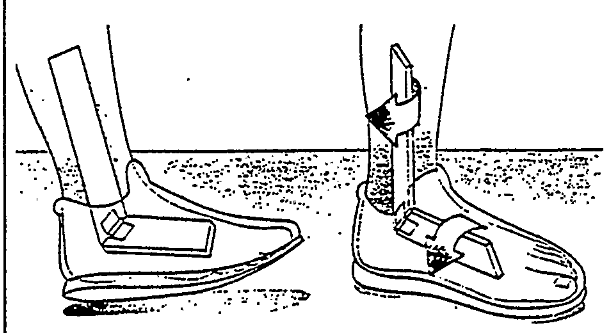

Figure 2.5: Initial Ground Contact During Heel-Toe Running Showing Supinated Foot Followed by Full Pronation of the Foot at Midstance (Left Foot) (adapted from Nike, 1989)

patella to be displaced, rotated or tilted medially. In principle, localized regions of the abnormal joint contact areas and/or contact forces may result, leading to abnormal joint contact stresses (Mow et al., 1990).

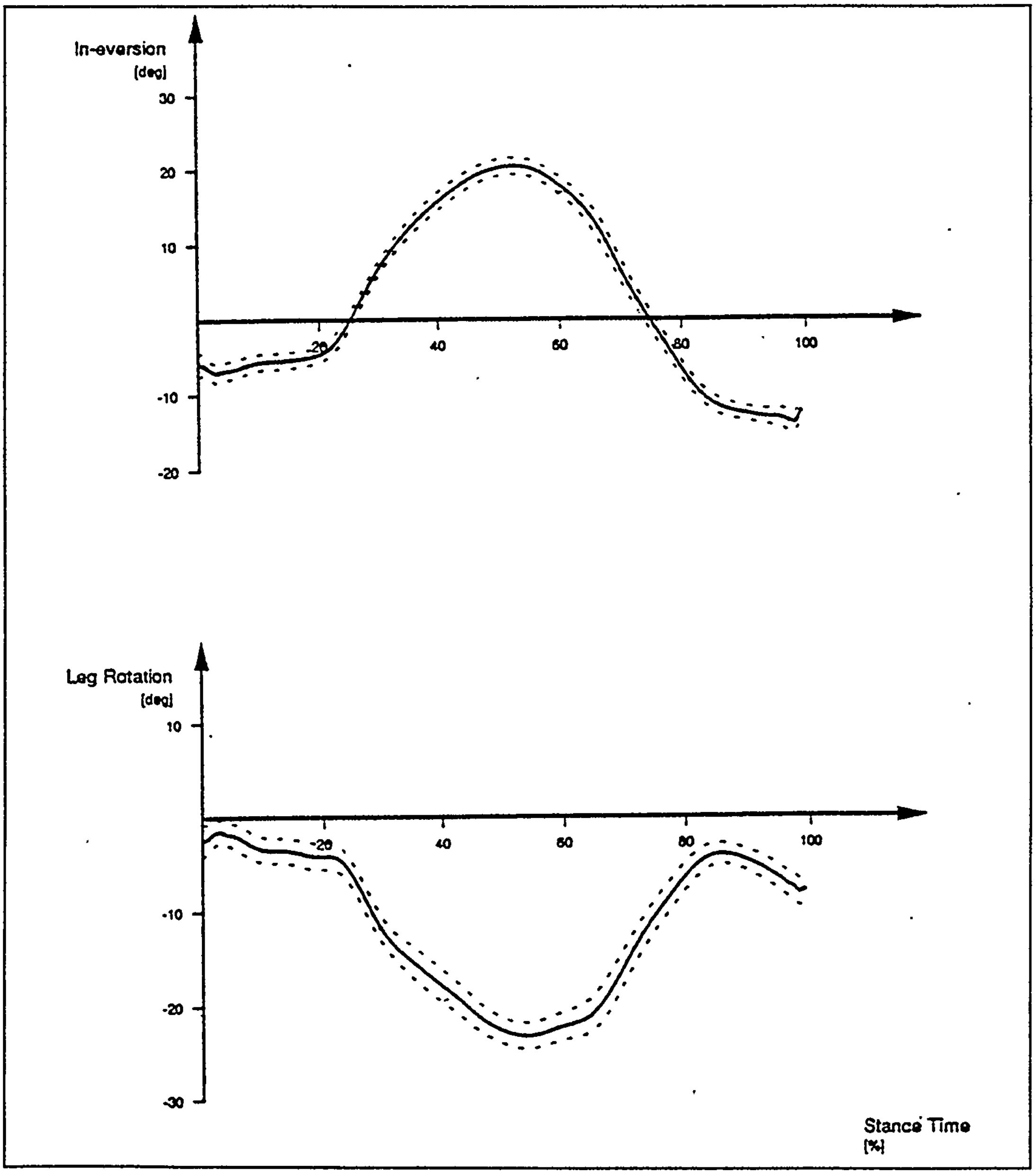

Figure 2.6: Foot Eversion and Internal Tibial Rotation for Stance Phase of Heel-Toe Running (mean ± S.E. plotted) (from Nigg et al., 1993)

Nigg and co-workers (1993) have shown a coupling of eversion of the foot to internal lower leg rotation (Figure 2.6). Thirty subjects were tested and showed an average maximal eversion of 28 ± 7.2° and a maximal internal lower leg rotation was 21.8 ± 8.4°. A regression analysis showed that correlation between these two variables to be strong ($r^2=0.991$, $p<0.0001$). This supports the notion that there is a coupling of foot eversion to axial rotation of the lower leg.

The effects of arch height on the motions of the lower extremity during running have also been studied (Nigg et al., 1993). Arch height did not influence maximal eversion nor did it have an effect on maximal internal rotation of the lower leg during stance. However, the amount of transfer of eversion of the foot to internal lower leg rotation was found to increase significantly with increasing arch height. This finding may have ramifications with respect to knee injuries, as an increased internal rotation of the tibia has been speculated to be a contributing factor in the onset of PFPS. It is unclear in the literature as to whether PFPS is related to arch height. One thought is that the high-arched, stiff foot may actually be one factor related to knee problems in runners through the transfer of motion from the foot to the lower leg. It may be speculated that a high-arched foot has a more vertical inclination of the subtalar axis and a low arched foot has a more horizontal axis. Arch height did have a substantial influence on the transfer of eversion of the foot to internal leg rotation (Nigg et al., 1993). This is only one possible mechanism among many that may lead to axial rotation of the tibia with respect to the femur.

Excessive pronation has been statistically linked with patellofemoral pain syndrome (Bahlsen, 1988). In a prospective study using 146 subjects (only 95 remaining after attrition), excessive pronation was statistically linked to PFPS. However, only four subjects were actually diagnosed with the condition and it has been recognized by the researcher that this study required larger and more homogeneous groups to obtain more meaningful results.

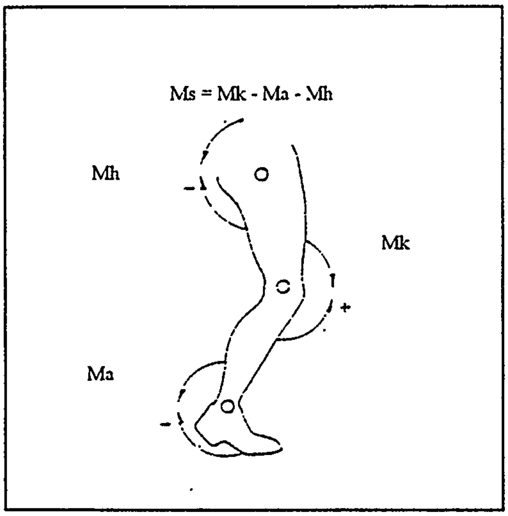

Figure 2.7: Support Moment Shown as the Sum of All Moments at the Hip, Knee and Ankle Joints (from Winter, 1980)

During the support phase of gait, the lower limb must resist collapse by producing a resultant extensor moment at the ankle, knee and hip joints (Figure 2.7). As described in Winter (1980), it is possible to obtain a net extensor moment of the lower limb by using different joint moments at the ankle, knee and hip. If there is an injury around a joint, the support moment will be achieved mainly by the uninjured joints. Hebert and co-workers (1994) used Winter's theory and suggested that people with PFPS reduce the stress on their patellofemoral joint by decreasing the use of their knee extensor muscles during functional activities. Twenty-two subjects (11 with PFPS and 11 without) were used to test this theory using squatting tests. Kinematic and kinetic data were collected for three conditions designated as natural, imposed and tip toes. The objective of all of the conditions was to squat to a position of 90° of knee flexion and maintain this position for five seconds. The imposed test required the subject to equally distribute their body weight on each foot and the natural test required no such control. The tip toes test was the same as the natural test, however, all of the subject's weight was distributed on their forefeet. It was reported that PFPS subjects did not show a strategy that tended to decrease the knee extensor moment. In fact, there was a significant increase in knee extensor moment of PFPS subjects during the tip toes test. It should be noted that this study only considered static posture tests and did not address the dynamic nature of the problem. No literature was found comparing the resultant joint moments at the ankle, knee and hip between normal and PFPS subjects during running.

Research has been performed on the relationship of knee pain and the movement of the lower limb (Dillon et al., 1983, Radin et al., 1991, Callaghan and Baltzopoulos, 1994). Radin and co-workers (1991) examined the hypothesis that appropriate and timely neuromuscular limb motions play an important role in the maintenance of joint health. Two groups of subjects, 18 exhibiting knee joint pain and 14 asymptomatics, underwent a full kinematic and kinetic analysis. The knee joint pain group was chosen as subjects that had a history of activity-related pain, negative radiographs, no history of previous trauma to the lower extrmities and no evidence of inflammatory arthritis. The results showed that the knee pain group had statistically significant higher velocity of the ankle at heel touchdown and angular velocity of the lower leg. The authors speculted that this increased repetitive impulse loading, which they termed "microklutiness", may be related to the osteoarthritic process. However, studies on the association of activity-related knee pain (e.g., running) to degenerative joint disease (Lane et al., 1986, Panush et al., 1986, Eichner, 1989, Konradsen et al., 1990) have all shown that there is no relationship between long distance running and osteoarthritis.

Dillon and co-workers (1983) studied the walking kinematics of groups of women with and without signs of chondromalacia patellae. It was found that the chondromalacia volunteers exhibited less maximal knee flexion during the stance phase and an increased external rotation of the femur during the swing phase. Also, the symptomatic group displayed a significantly larger femoral rotation immediately preceding heel contact. Although the researchers called the symptomatic group the chondromalacia group, they should be called the anterior knee pain group. These subjects were only diagnosed with pain and no attempt was made to associate this symptomatic pain with any clinical signs.

Callaghan and Baltzopoulos (1994) looked at kinematic and kinetic parameters in patients with and without anterior knee pain. Two groups of 15 female subjects (15 asymptomatics and 15 diagnosed with anterior knee pain) volunteered to perform 10 barefoot walking trials while both force plate and film data were collected. The results showed that the asymptomatic subjects had a significantly higher lateral force compared to the anterior knee pain group. However, the pain group had a higher time taken to achieve maximal lateral force and a higher time taken to achieve maximal rearfoot angle (pronation). This may suggest that the discriminating factor for the onset of PFPS, at least within a population of low level recreational females, may be the extended time taken to achieve maximal lateral force and not maximal lateral force itself. The results from this study do not agree with previous theories that lateral force is larger in patients with lower limb dysfunction and care should be taken when comparing these results for groups of different recreational status.

2.2.2.2 Anatomy

The Q-angle is the acute angle of the pull of the patellar tendon with respect to femur and the centre of the patella (Woodall and Welsh, 1990). The Q-angle is typically measured in a standing position using a goniometer and anatomically placed lines. The first line is drawn connecting the points of the anterior superior iliac spine (ASIS) to the centre of the patella. The second line is made connecting the mid-point of the patella to the tibial tuberosity (Figure 2.8). The Q-angle has been a variable of interest related to running injuries (Messier and Pittala, 1988, Messier et al., 1991, Caylor and Fites, 1993). A normal Q-angle has been considered around 16^0 for females and 10^0 for males, with greater than 20^0 being considered abnormal for both males and females (Roy and Irvin, 1983). Functionally speaking, a larger Q-angle may lead to a more oblique pull of the patella by the quadriceps muscles, disrupting the patella's natural motion within the femoral groove. This may lead to a change in contact areas/pressures within the patellofemoral joint and cause pain.

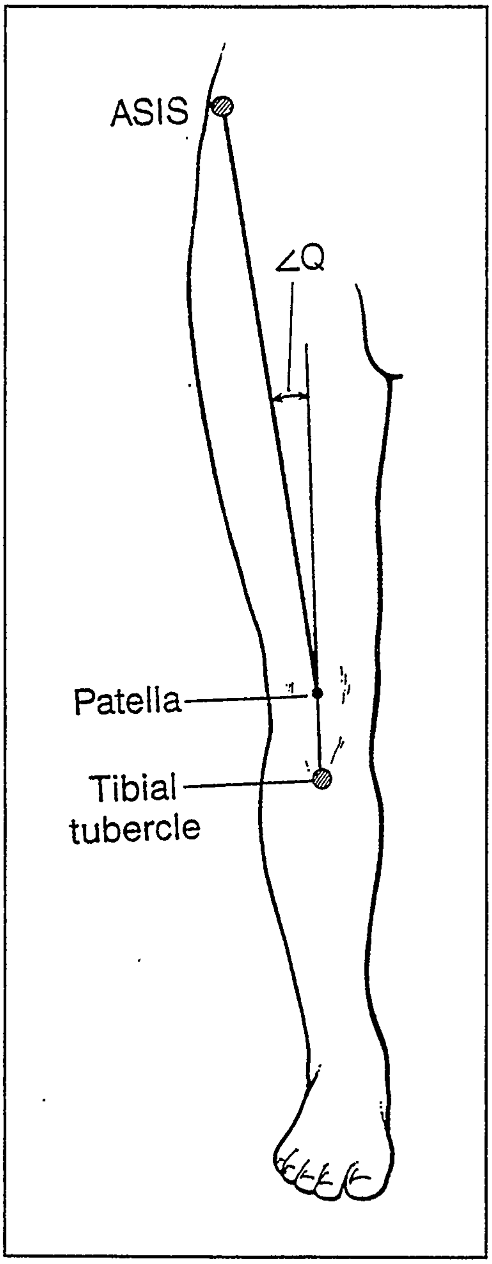

Figure 2.8: Quadriceps Angle (Q-angle) Measurement for Right Leg Using Location Points of Anterior Superior Iliac Spine (ASIS), Centre of the Patella (Patella) and the Insertion of the Patellar Tendon on the Tibia (Tibial Tubercle) (from Woodall and Welsh, 1990)

One study showed the Q-angle to be a strong discriminator between runners with and without PFPS (Messier et al., 1991). Thirty-six subjects (16 PFPS and 20 asymptomatic) underwent an anthropometric, biomechanical and isokinetic evaluation. The average Q-angles were 17.19 ± 0.60^0 and 11.05 ± 0.38^0 for the PFPS and asymptomatic groups, respectively. Another study reported that there was no significant difference in Q-angle between a group with anterior knee pain (12.4 ± 5.1^0) and an asymptomatic group (11.1 ± 5.5^0) (Caylor and Fites, 1993). The authors of this second study agree that these results are in conflict with many other studies of the past. However, the study may suggest that anterior knee pain can exist in a patient population without a significantly higher Q-angle than in an asymptomatic population.

There have been studies done attempting to relate Q-angle to rearfoot motion parameters. In a study, using twenty asymptomatic females, Kernozek and Greer (1993) found that Q-angle was not statistically related to rearfoot motion parameters during walking (i.e., maximal pronation). Using reflective markers at the locations of the anterior superior iliac spine, the centre of the patella and tibial tubercle, static and dynamic Q-angle measurements were made on 20 women with no history of lower extremity injury. In order to minimize for errors in Q-angle mesurement due to movement out of plane as well as patellar movement, the authors ony selected dynamic angle measurements at heel-strike and midstance. However, at midstance there is most likely an out of plane movement (i.e., internal rotation of the lower leg with respect to the femur), which may lead to a problem when only analyzing in the frontal plane. Relative motion of the skin markers with repsect to the underlying bone may also pose an accuracy problem when trying to analyze kinematic data (Reinschmidt, submitted). It was found that a greater Q-angle did not predispose an individual to a greater maximal pronation. Dynamic Q-angle (16.00 ± 6.32^0), measured at midstance, was less than static Q-angle (18.32 ± 9.38^0), but neither was related to the rearfoot parameters measured. Although both the Q-angle and maximal pronation are not related to each other, each variable may be contributing to PFPS individually. Thus, one must look at both factors when attempting to assess factors that may be associated with PFPS.

Orthotics have been shown to change Q-angle measurements (D'Amico and Rubin, 1986). Twenty-one patients had both their limbs measured for Q-angle with and without orthotics. All 42 lower limbs either showed a reduction or no change to Q-angle when the orthotic was used. This reduction ranged from 0 to 8^0 with an average decrease of 6^0. The authors believe that the decrease in Q-angle is a cause of changing the position of the foot. It is theorized that by placing a wedge under the medial side of the foot, there is a reduction in pronation of the foot. Since a relationship between eversion of the foot and internal rotation of the tibia exists, during running (Nigg et al., 1993), a reduction in the amount of pronation may lead to a decrease in the amount of internal tibial rotation. This reduction in internal rotation of the tibia may be associated with a decreased excursion of the patella medially and thus a decrease in the Q-angle. This was not substantiated in the research and further studies on the effects of orthotics on lower limb dynamics are warranted.

2.2.2.3 Training

In a review of epidemiological literature on running related injuries, van Mechelen (1992) stated that training factors associated with running injuries include:

1. previous injury
2. lack of running experience
3. running to compete
4. excessive weekly running distance

Factors that have been shown not to be significantly related to running injuries include age, gender, body mass index, running on hard surfaces, running hills, participation in other sports, time of year and time of day (van Mechelen, 1992). Other factors such as warm-up, running frequency, shoes and insole orthoses are speculatd to be associated with running injuries, but have not been substantiated in the literature (van Mechelen, 1992).

A closer review of larger epidemiological studies (n > 450) shows a relationship between running injuries and training error (Jacobs and Berson, 1986, Marti et al., 1988, Macera et al., 1989, Walter et al., 1989). Table 2.3 below is a summary of the contributing factors in these studies:

Table 2.3: Training Variables Related to Running Injuries From Four Epidemiological Studies with Sample Sizes Greater Than 450 Subjects

			RELATED FACTORS					
Author(s) (date)	n	location	1	2	3	4	5	6
Jacobs and Berson (1986)	451	race	✓		✓	✓	✓	
Marti et al. (1988)	4358	race	✓				✓	✓
Marcera et al. (1989)	583	clinic	✓		✓			✓
Walter et al. (1989)	1680	race	✓	✓	✓			✓

Related Factors:
1. weekly running distance
2. daily running distance
3. number of days run

4. running speed
5. training to compete
6. previous injury

note:** ***the above related factors are based on many papers and all are statistically significant at p=0.05 or smaller

All four studies presented in the above table show that increased weekly running distance to be a factor related to injury. Also three of the studies found that number of days run per week and previous injury to be contributing factors. It is clear from the epidemiological data that training error is a major contributing factor associated with running injuries. Therefore, any study investigating the biomechanics of running injuries should control for weekly running distance, number of days run per week and previous injuries. Other confounding factors that have not yet been verified as associated factors, such as running shoes or use of foot orthoses, should also be controlled for. Factors which have been shown not to be related such as age, gender, surface and running hills do not have to be controlled for. However, this information should be gathered via a questionnaire for every subject for future analysis.

2.3 Summary

Evidently, PFPS presents a problem within a running population. Mechanisms such as increased internal tibial rotation with respect to the foot ($\Delta\rho_{max}$), increased internal tibial rotation with respect to the femur ($\Delta\psi_{max}$), a larger patellofemoral joint contact force (F_{pfmax}), a larger Q-angle and a higher weekly running distance have been proposed as factors that may be associated with the onset of PFPS. For these variables, potential mechanisms which could be responsible for the onset and development of PFPS are available. To the best of the author's knowledge there have been no studies which determine the relationship between the above factors and PFPS in a running population. A three-dimensional kinematic and kinetic analysis of running style is required to see if these proposed mechanisms are related to PFPS.

3. Methods

3.1 Subject Selection

The purpose of this project was to analyze whether there were differences in dynamic, anatomical and/or training variables between subjects with and without patellofemoral pain. Three groups of runners were analyzed using a retrospective study design. These groups included:

PFPS-group (PFPS): group of subjects with patellofemoral pain syndrome at time of study, with no other injuries to the lower extremity in the past three months.

former PFPS-group (Past-PFPS): group of subjects with patellofemoral pain syndrome in the past, with no other injuries to the lower extremity in the past three months.

asymptomatic-group (AS): group of subjects that never had patellofemoral pain syndrome, with no other injuries to the lower extremity in the past three months.

Data were collected for 57 subjects (n=21 PFPS; n=16 Past-PFPS; n=20 AS). Two subjects were discarded due to poor data, thus making the total n= 55 (n=20 PFPS; n=15 Past-PFPS; n=20 AS). Original sample size calculations, using differences in tibial rotation as the variable of interest ($X_{diff}=5^0$; S.D.= $\pm$ 5^0; α = 0.05; β = 0.10) yielded a sample size of approximately n=17/group. Injured and past injured volunteers were recruited via medical records from the University of Calgary Sports Medicine Clinic. Asymptomatic volunteers were recruited from a local running shoe store. The criteria for entry into the study were as follows:

All volunteers:

1. ran an average weekly distance between 10-90 km
2. were between the ages of 20-50 years
3. had no injuries to the testing leg at the time of study
4. had no prior knee surgery or diagnosis of joint disease
5 had been an active runner for at least six months prior to the study or prior to their injury

PFPS and Past-PFPS volunteers:

1. had diagnosis of PFPS which was not related to patellar tendinitis, quadriceps tendinitis, peripatellar tendinitis or prepatellar bursitis.
2. had PFPS that was related to a "repetitive" trauma and was not acute in nature
3. rehabilitation (Past-PFPS group only) was related to rest, physiotherapy

and/or orthotic prescription

A comprehensive review of each medical record was required to properly select volunteers for the study. Subjects were considered for contact only if they had signed a consent form releasing their medical information for the purposes of research. Initial subject contact was done via a telephone conversation. Questions asked at this time (i.e., weekly running distance, age) screened out subjects not fitting the study criteria. Subjects fitting the criteria were then asked to volunteer one hour of their time for an analysis of their running style. Prior to any data collection, an Ethics Committee approved consent form was signed and witnessed.

3.2 Selection of Variables

Five variables were selected for analysis for which a possible functional relationship with the onset of PFPS was available. They included:

1) maximal tibial rotation with respect to the foot ($\Delta\rho_{max}$)
2) maximal tibial rotation with respect to the femur ($\Delta\psi_{max}$)
3) maximal patellofemoral joint contact force (F_{PFmax})
4) Quadriceps-angle (Q-angle)
5) Weekly Training Distance (weekly)

A summary of the proposed mechanism responsible and the mechanical reason for each of the above variables is given in Table 3.1.

Table 3.1: Possible Mechanisms and Mechanical Reasons for Five Functional Variables Associated With Patellofemoral Pain Syndrome in Runners

FUNCTIONAL VARIABLES	MECHANISM	MECHANICAL REASON
1) tibial rotation with respect to the foot ($\Delta\rho_{max}$)	• excessive eversion of the foot transferred to excessive internal tibial rotation and the patella is displaced/rotated changing the contact/pressure pattern on the articulating surface of the patella	• pressure magnitude increased and/or location of contact area changed to location which is not loaded during normal daily activities
2) tibial rotation with respect to the femur ($\Delta\psi_{max}$)	• increased relative tibial rotation with respect to the femur and the patella is displaced/rotated, changing the contact/pressure pattern on the articulating surface of the patella	• pressure magnitude increased and/or location of contact area changed to location which is not loaded during normal daily activities

3) patellofemoral joint contact force (**F_{PFmax}**)	• increased compressive load applied to the patellofemoral joint	• change in stress within the patellofemoral joint (assuming that contact area remains constant or decreases), leading to pressure increase beyond physiological limits capable by tissues (e.g., cartilage)
4) Q-angle	• increased lateral pull of the patella	• change in contact/pressure patterns on articulating surface not allowing proper tracking in the femoral groove
5) weekly running distance	• higher distance run per week compared to other runners	• chronic overload on tissues of patellofemoral joint due to repetitive/cyclic motion of running, causing tissue fatigue/wear, leading to subchondral bone pain

The first three functional variables were categorized as *dynamic* variables, the fourth was categorized as an *anthropometric* variable and the final was categorized as a *training* variable.

3.3 Data Collection

3.3.1 Anthropometric Measurements

Q-angle was measured using a goniometer. The Q-angle was represented as the angle between the line connecting the anterior superior iliac spine (ASIS) to the centre of the patella, and the line connecting the centre of the patella to the insertion of the patellar tendon in the tibial tuberosity (Figure 2.8). Subjects were asked to place their feet approximately hip width apart with their toes pointing forward. Their quadriceps muscles were relaxed and their knees were in a fully extended position. One arm of the goniometer was placed and held at the anterior-superior iliac spine (ASIS). The centre of the goniometer was placed to a point corresponding to the centre of the patella and the lower arm was rotated until it corresponded with a point of the insertion of the patellar tendon on the tibial tuberosity. This measurement was recorded in degrees (^{0}).

3.3.2 Kinematic and Kinetic Measurements

Three dimensional (3-D) kinetics and kinematics of the affected limb were quantified for the PFPS and Past-PFPS groups. The asymptomatic group only required one limb to be analyzed. The 3-D spatial positions of the upper leg, lower leg and foot segments were determined using nine reflective markers attached to the skin with adhesive tape (Figure 3.1). The markers were attached at the following locations: A =

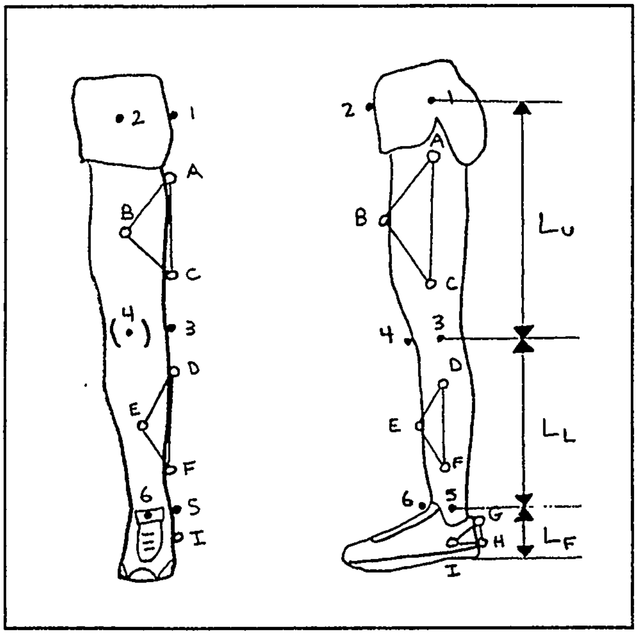

Figure 3.1 : Anterior and Lateral Views of Skin Marker Locations on Left Lower Limb Including Joint Centre Markers (1 to 6) and Segment Markers (A to I) (adapted from Nigg et al., 1993)

proximal-lateral upper leg, B = mid-anterior upper leg, C = distal-lateral upper leg, D = proximal-lateral lower leg, E = mid-tibial crest, F = distal-lateral lower leg, G = on the posterior shoe-upper calcaneus, H = on the posterior shoe-lower calcaneus, and I = on the lateral side of the shoe below the lateral malleolus. Six joint centre markers used for a neutral standing trial were located at: 1 = at the greater trochanter, 2 = on the anterior leg just below the ASIS, 3 = on the lateral knee, 4 = at the centre of the patella, 5 = on the lateral malleolus, 6 = on the shoe centre of the tongue.

The three-dimensional spatial positions of the markers were collected using four electronically shuttered, high-speed video cameras (NAC MOS-TV, V-14B, Japan) equipped with 12.5-75 mm zoom lenses (Cosmicar, Japan) and a VP310 video processor (Motion Analysis Corporation, Santa Rosa, CA). The cameras were located in an umbrella configuration, with the first camera located anterior, the second camera located lateral and slightly anterior, the third camera located lateral and slightly posterior, and the fourth camera located posterior to the plane of progression of the subject (Figure

3.2). The sampling frequency was set at 200 frames/s and the exposure time at 1/2500 s. System calibration was achieved using a calibration frame containing eight control points. The calibration volume closely matched the volume of interest. A two second calibration trial was collected after which the cameras were not moved for the remaining running trials. The raw data was stored on a SUN 3/280 computer.

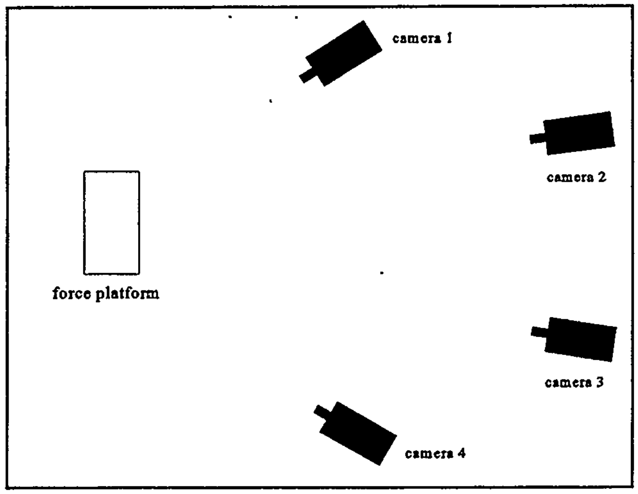

Figure 3.2: Camera Positions in Umbrella Configuration Around Force Platform

In order to attain the positions of markers A to I with respect to the joint centre markers (1 to 6) a standing trial was used as a baseline. The standing trial was recorded using the video system (200 Hz, 2 sec sample) and required the subject to stand in a neutral position with markers on the joint centres of the ankle, knee and hip. The neutral position was defined as the subject standing with feet pointing anteriorly and approximately hip width apart. The knee and hip were in a fully extended position with the ankle joint at approximately a 90° angle. The 3-D orientation of each of the markers A to I with respect to the joint centres were calculated using a computer algorithm programmed in MATLAB (The Math Works, Inc, Natick, Mass.) (see Appendix). The length of each of the three segments of the lower limb were measured using a digital calliper. The length of the upper leg (L_u) was represented by the distance between the greater trochanter and the centre of the knee joint. The lower leg length (L_l) was measured between the centre of the knee and the lateral malleolus. The length of the foot (L_f) was measured between the lateral malleolus and the ground (Figure 3.1). All of the above information was necessary in order to make a transformation file used to relate the marker based coordinate system to a meaningful anatomical segmental coordinate system for the foot, lower leg and upper leg. The axes directions of the anatomical coordinate systems were "x" representing anterior-posterior, "y" representing superior-inferior and "z" representing medial-lateral. After the standing trial was collected, the joint centre markers (1 to 6) were then removed for the running trials that followed.

The kinetic data during running was collected using a force plate (Kistler AG, Winterthur, Switzerland) mounted flush with the floor in the middle of a 30m runway. The force data was sampled at 1000Hz. The subjects were given several practice trials to ensure that the foot landed with a natural running style on the force plate. Running speed (4.0±0.2 m/s) was monitored using two photocells at shoulder height. Synchronous data collection for the video system and the force plate was triggered as the subject ran past the first photocell. A total of five good trials were collected per subject. A trial was repeated if the running speed was not within the proper range, the foot did not land on the force plate or the subject altered his/her running style prior to hitting the force plate with the foot.

3.4 Data Analysis

3.4.1 Kinetic and Kinematic Data

Video data was processed using Expert Vision Three-Dimensional (EV3D) (Motion Analysis Corporation, Santa Rosa, CA) software. A direct linear transformation method (DLT) was performed to determine three-dimensional spatial coordinates of each marker from the two-dimensional data collected. Data were tracked for a period corresponding to 10 frames before and after contact with the force plate. Filtering of data to remove unwanted noise was performed using a fourth-order low pass Butterworth Filter with cut-off frequencies of 12 and 50 Hz for the kinematic and kinetic data respectivley. All data were imported into Kintrak 4.0 (The University of Calgary, Calgary, Alberta) for further analysis. Three good trials were used per subject for analysis of the kinematic variables ($\Delta\rho_{max}$, $\Delta\psi_{max}$, F_{PFmax}).

Three-dimensional joint attitude and angular motions were represented using a Joint Coordinate System (JCS) implemented in Kintrak 4.0 (The University of Calgary, Calgary, Alberta). This JCS consisted of an axis fixed in the proximal segment, an axis fixed in the distal segment, and a "floating" axis not fixed in either segment which moved in relation to both. Relative rotation of one segment with respect to the the other (e.g., axial rotation of the tibia with repsect to the femur) was represented as a spin of one segment (e.g., tibia) about its own fixed axis while the other segement (e.g., femur) remained stationary. The magnitude of this rotation was measured by an angle formed between the floating axis and a reference line embedded in each segment (Grood and Suntay, 1983).

The kinematic variables measured in this study were calculated from 3-D positions of markers paced on the skin and this may pose a problem. It is thought that movement of the markers on the skin may not represent movement of the underlying bone. This may be an extreme problem for markers placed on the skin of the upper leg due to the large quantities of muscle and fat between the skin markers and the femur (Reinschmidt et al., submitted). Therefore any data on movement of the upper leg may not represent true movement of this rigid segment. Reinschmidt and co-workers (submitted) compared skin marker movement to intercortical bone pin movement (pins inserted directly into the bones of the tibia and femur) during heel-toe running. Initial results from this study indicated that there was a difference in kinematic parameters (i.e., $\Delta\psi_{max}$) when comparing skin to bone markers. The shape agreement of the curves was subject dependent, with some subjects having a close match and some having a poor match. However, in general, the bone pin movement showed similar patterns to the skin marker movement of internal followed by external rotation of the tibia with respect to the femur during heel-toe running. In summary, if one is attempting to compare an absolute value of tibial rotation with respect to the femur and relate it to bone movement, the skin marker method used in this present study would not be accurate as it has been shown that the magnitude of motion is different for the bone pin method.

In the present study, comparisons were done for maximal tibial rotation with respect to the femur. If the groups used in the study were homogeneous, morphologically speaking, and the marker placement locations were consistent on the upper and lower leg, then it may be proper to compare values of tibial rotation. The absolute number could not be used to describe the actual movement of the bones, however, the pattern of movement could be analyzed and comparisons could be done across groups.

Typical angular motions of the two rotational variables are shown in Figures 3.3 and 3:4. A typical motion of the tibia with respect to the foot is shown in Figure 3.3. From initial contact to approximately 55% of stance the tibia internally rotates with respect to the foot, then externally rotates until toe-off. Maximal internal rotation ($\Delta\rho_{max}$) was calculated as the difference from initial contact to a point of maximum rotation.

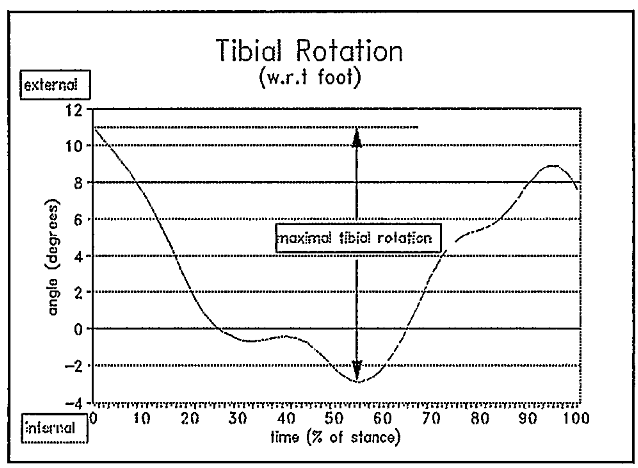

Figure 3.3: Typical Curve for Heel-Toe Running Representing Tibial Rotation with Respect to the Foot (subject #1, trial #23)

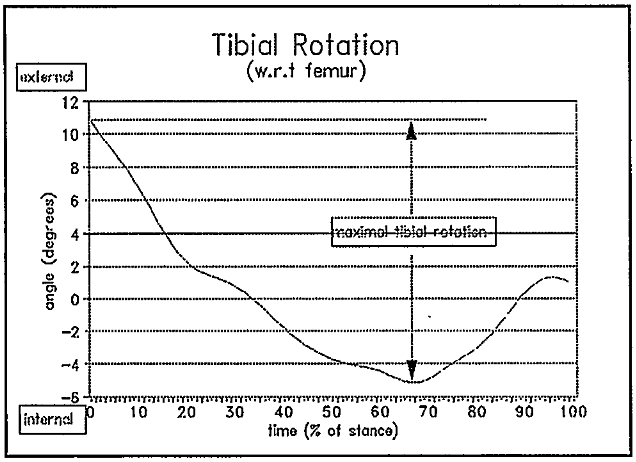

Figure 3.4: Typical Curve for Heel-Toe Running Representing Tibial Rotation with Respect to the Femur (subject #1, trial #23)

A typical motion of the tibia with respect to the femur is shown in Figure 3.4. At touchdown the tibia is externally rotated with respect to the femur and then undergoes an internal rotation until approximately 65% of stance, after which it externally rotates until toe-off. Maximal internal rotation ($\Delta\psi_{max}$) was calculated as the difference in angle from initial contact to maximal internal rotation.

3.4.2 Maximal Patellofemoral Joint Contact Force (F_{PFmax})

Patellofemoral joint contact forces were modelled using a 2-D sagittal plane model of the knee. This model was adapted from Scott and Winter (1990), with a few modifications (Figure 3.5). The assumptions of the model were as follows:

1. Force on the patellofemoral joint was a point contact force acting at the centre of contact between the patella and femur.

2. The system was reduced to motion in the sagittal plane.

3. The mass of the patella (i.e., moment of inertia) was assumed negligable.

4. The force produced by the muscles was proportional to their physiological cross-sectional area (PCSA). It was recognized that other factors such as force-length, force-velocity, series elastic component and parallel elastic component affect the force generated by a muscle, but these were not considered in the model. PCSA of muscles used in this model were averaged from two cadaveric studies (Alexander and Vernon, 1975, Wickiewicz et al., 1983). The size of the subjects used in this study were similar to the specimen used by Alexander and Vernon (1975) (mass = 64 kg and height = 166 cm). No information was available in the paper by Wickiewicz and co-workers (1983) on the mass and height of their specimens.

5. Ligamentous forces were ignored.

6. Moments at the knee and ankle were calculated using a standard inverse dynamics approach. (note: only moments about sagittal axis were considered)

7. Since the force produced within the patellofemoral joint depended on the orientation of the quadriceps tendon and the patellar tendon with respect to the femur at any given time, this was modeled as a function of knee flexion angle (van Eijden et al., 1985).

8. The patella was not considered a frictionless pulley, therefore the force ratio of the quadriceps tendon to the patellar tendon was modeled as a function of knee flexion angle (van Eijden et al., 1987).

9. The moment arms of the muscles in the model were attained from the literature. The patellar tendon moment arm varied with knee flexion angle (van Eijden et al., 1987). At 0^0 of knee flexion the moment arm was approximately 4.2 cm and maximized at 40^0 of flexion at 5.0 cm. From 40^0 to 120^0 the moment arm length decreased again to approximatley 4.5 cm. Therefore two separate linear equations were used to model the moment arm length of the patellar tendon:

$$\text{a) } d_{pt} = .00035 \times ANG_{kn} + .04 \qquad \text{(if knee angle} < 40^0\text{)}$$

or

$$\text{b) } d_{pt} = -.000025 \times ANG_{kn} + .051 \qquad \text{(if knee angle} > 40^0\text{)}$$

Due to the lack of data on the moment arm length of the Achilles tendon with respect to the position of the foot, this moment arm was estimated to be constant at 4.6cm (Spoor et al.,1990).

10. The ankle was modeled with only the plantarflexors functional (i.e., no co-contraction of the dorsiflexors). This was done in order to provide a unique solution to the indeterminacy problem. The plantarflexors modeled included the gastrocnemius, soleus and plantaris muscles.

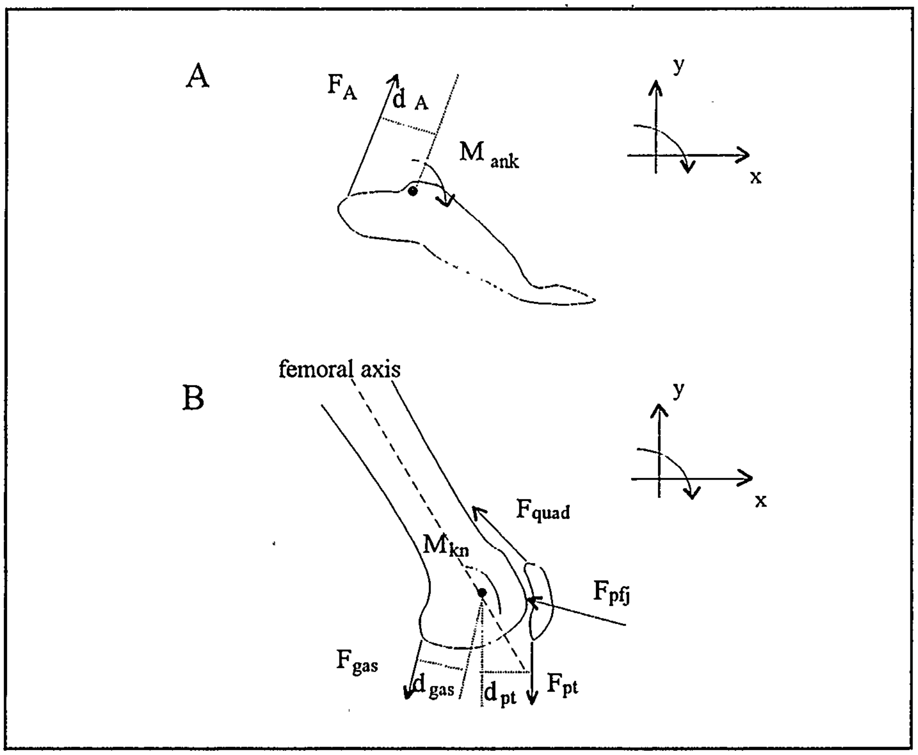

Figure 3.5: Free Body Diagram of the **A)** Ankle Model and **B)** Knee Model to Predict F_{PF} During Heel-Toe Running (adapted, with changes, from Scott and Winter, 1990).

11. The knee was modeled using both extensors and flexors. The extensors of the knee which included the rectus femoris, vastus lateralis, vastus medialis and vastus intermedius were grouped into produce the quadriceps force ($\mathbf{F}_{quad}$). The flexors of the knee included only the gastrocnemius. Only one knee flexor was included in the model due to the indeterminancy problem. Because no co-contraction was assumed at the ankle joint, a unique solution was possible for the gastrocnemius force. The force produced by the gastrocnemius in the ankle model was translated into the knee model to produce a unique solution at this joint as well.

Each of the variables used in the calculation is defined below with units given in parentheses:

$\vec{S}_A$ = stress in the Achilles tendon (N/m^2)

$\vec{M}_{ank}$ = resultant sagittal plane ankle joint moment (Nm)

$\vec{M}_{kn}$ = resultant sagittal plane knee joint moment (Nm)

d_A = moment arm length of the Achilles tendon (m)

$PCSA_{sol}$ = physiological cross-sectional area of soleus muscle (m^2)

$PCSA_{gas}$ = physiological cross-sectional area of gastrocnemius muscle (m^2)

$PCSA_{pln}$ = physiological cross-sectional area of plantaris muscle (m^2)

$\vec{F}_{gas}$ = force produced by the gastrocnemius muscle (N)

$\vec{F}_{pt}$ = force produced by the patellar tendon (N)

d_{gas} = moment arm length of the gastrocnemius muscle at the knee (m)

d_{pt} = moment arm length of the patellar tendon (m)

$RAT_{pt/quad}$ = force ratio of the quadriceps force to the patellar tendon force ( )

$\vec{F}_{quad}$ = force produced by the quadriceps tendon (N)

$\vec{F}_{PFJ}$ = patellofemoral joint contact force (N)

ANG_{kn} = angle of the tibia with respect to the femur (degrees) (0^0 = full extension)

The following equations were used to calculate patellofemoral joint (PFJ) contact forces. The force in the gastrocnemius muscle was calculated by:

$$\vec{S}_A = \frac{\vec{M}_{ank}}{(PCSA_{sol} + PCSA_{gas} + PCSA_{pln}) \times d_A}$$

and

$$\vec{F}_{gas} = \vec{S}_A \times PCSA_{gas}$$

The patellar tendon force was calculated using:

$$\vec{F}_{pt} = \frac{\vec{M}_{kn} + (\vec{F}_{gas} \times d_{gas})}{d_{pat}}$$

The force exerted by the quadriceps was modeled as a linear system that was dependent on knee flexion angle using the following equation (Huberti et al., 1984):

$$RAT_{pt/quad} = -.01 \times ANG_{kn} + 1.2$$

Consequently, the force in the quadriceps tendon was calculated as a ratio of the force using:

$$\vec{F}_{quad} = \frac{\vec{F}_{pt}}{RAT_{pt/quad}}$$

Now the PFJ force could be calculated using this vector sum equation:

$$\vec{F}_{pfj} = \vec{F}_{pt} + \vec{F}_{quad}$$

A computer algorithm was used to calculate the patellofemoral joint contact force from initial contact to toe-off (see Appendix).

The inputs to the model included ankle moment (M_{ank}), knee moment (M_{kn}) and knee flexion angle (ANG_{kn}) over the whole period of stance phase. Figures 3.6 to 3.9 are typical curves seen for ankle moment, knee moment and knee angle for heel-toe running. The ankle

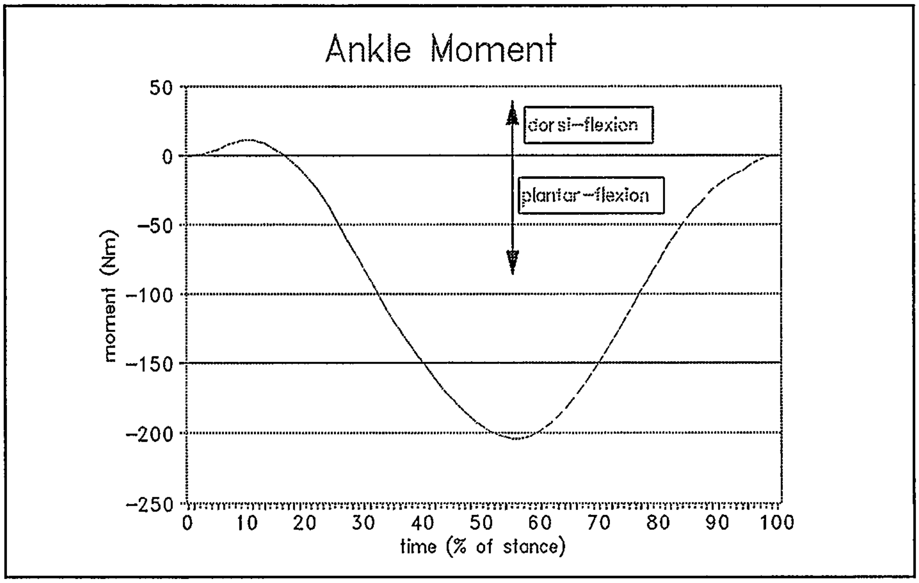

Figure 3.6: Sagittal Ankle Moment During the Stance Phase of Heel-Toe Running for a Typical Subject (subject #1, trial #23)

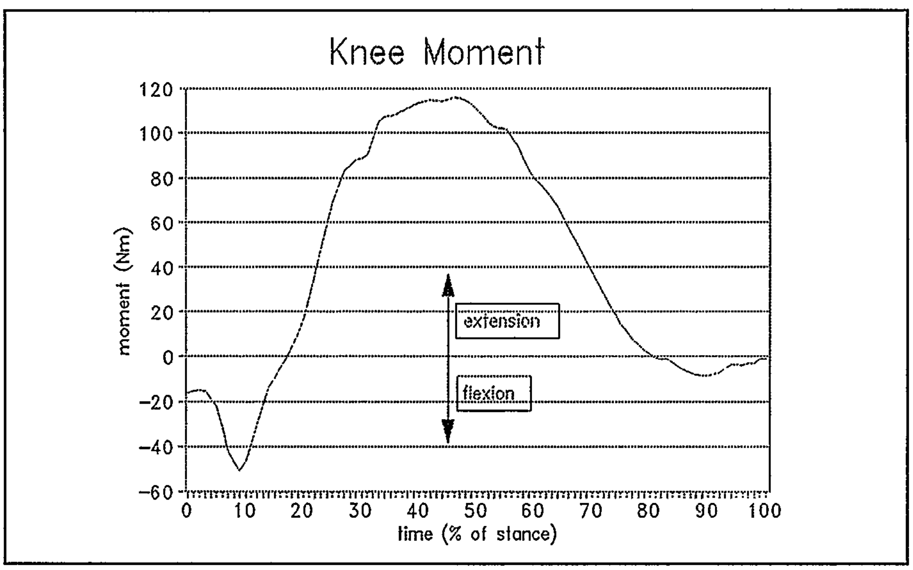

Figure 3.7: Sagittal Knee Moment During the Stance Phase of Heel-Toe Running for a Typical Subject (subject #1, trial #23)

moment displayed a small dorsi-flexion moment at touchdown, followed by a large plantar-flexion moment until pushoff (Figure 3.6).

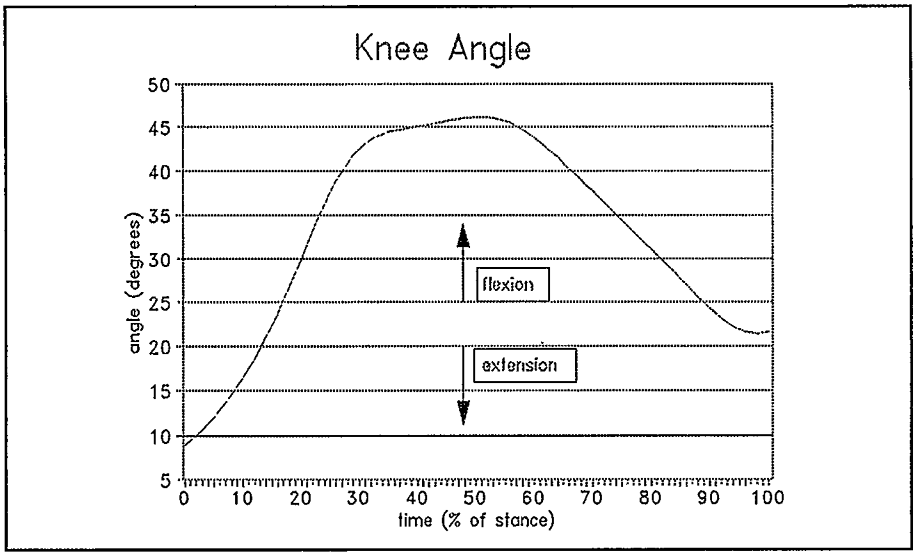

Figure 3.8: Sagittal Knee Angle (Tibia with Respect to the Femur) During the Stance Phase of Heel-Toe Running for a Typical Subject (subject #1, trial #23)

Generally, there was a period of knee flexion moment from 0 to 20 % of contact followed by a large extension moment from 20 to 80 % of contact, ending with another period of flexion moment (Figure 3.7). The angle of the knee with respect to the femur in the sagittal plane showed the typical action of slight flexion (almost full extension) at contact, followed by a period of flexion to approximately 45^0 at midstance and extension until push-off (Figure 3.8).

Maximal values of ankle moment, knee moment and knee flexion angle are shown for a sample of ten subjects from this present study and compared to various other studies in Table 3.2. Studies were chosen that represented heel-toe running patterns, with a running speed closely matching the running speed of the present study.

Table 3.2: Variable Comparisons of Maximal Ankle Moment, Maximal Knee Moment and Maximal Knee Flexion Angle to Past Studies (*** represents data not available).

Variable / Study	number of subjects (n)	running speed (m/s)	maximal ankle moment (Nm)	maximal knee moment (Nm)	maximal knee angle (^{0})
Present Study	10	4.0	225	112	44
Vaughan (1984)	1	5.4	***	***	50
Buczek and Cavanagh (1990)	7	4.5	201	288	44
Scott & Winter (1990)	1	5.1	140	160	***
Simpson & Bates (1990)	4	4.1	224	308	***

The values for maximal ankle moment and maximal knee angle correspond quite well with previous studies. However, maximal knee moment seems to be lower than previously found. One factor that may have lead to this was the definition of the knee joint centre. It is difficult to assess this point because specific details about location of knee joint centres were not described in the above literature.

All of the above inputs and some constant values (i.e., PCSA of muscles, moment

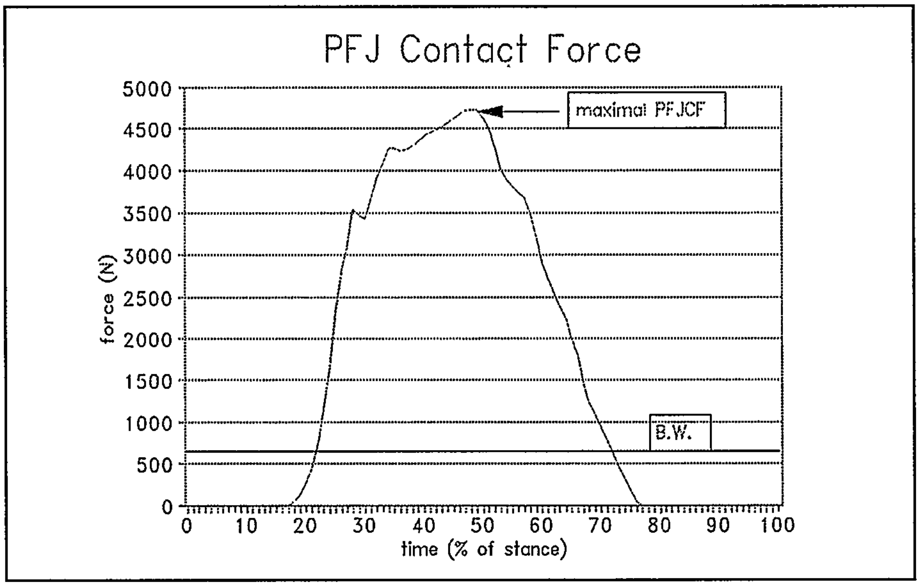

Figure 3.9:Patellofemoral Joint Contact Force (F_{PF}) During the Stance Phase of Heel-Toe Running for a Typical Subject (subject #1, trial #23)

arm lengths), were run through a computer algorithm to achieve the final output of Patellofemoral Joint Contact Force (F_{PF}). Figure 3.9 represents a typical curve of the PFJCF that corresponds, both in magnitude and shape, to the data presented by Scott and Winter (1990). This force rached a maximum for most subjects between 30 and 60% of the stance phase. For this particular subject, the maximal force (4750 N) corresponded to approximately 7.5 times body weight. Figure 3.9 displays a patellofemoral joint contact force of 0 N at the beginning and end of the stance phase. One constraint to this sagittal model included that the force is constrained to zero if the force in the patellar tendon was a negative value. Therefore, this model was not realistic in attaining information for the first 20 % and last 20 % of the stance phase of running.

3.4.3 Statistical Analyses

3.4.3.1 Reliability Measurements

All variables in this study were assessed for reliability. Three repeated measures on each variable were done on each subject. Reliability was assessed using Cronbach's Alpha reliability coefficient SPSS 5.0 (SPSS Inc., Chicago, Ill.). This measurement tested for "internal consistency" of each variable. This was based on the average correlation of the items within a test if the items were standardized to a standard deviation of one. An Alpha value of "1" represented high internal consistenecy (high reliability) and a value of "0" represented low internal consistency (low reliability).

3.4.3.2 Analysis of Variance

A multivariate analysis of variance (MANOVA) was used ($\alpha = 0.05$) to see if there were any differences across the three groups for all the variables of interest SPSS 5.0 (SPSS Inc., Chicago, Ill.). If any differences were found, these differences were then assessed using individual one-way ANOVA's ($\alpha = 0.05$) followed by Scheffé's post-hoc analysis to pinpoint the differences. Tests of homogeneity of variance were performed to determine if constant variance existed across the three groups. The F-test is considered a fairly robust test and could deal with small deviations from homogeneity of variance or disruptions to normality, if the sample sizes are similar across the groups.

3.4.3.3 Stepwise Discriminant Analysis

A procedure called Stepwise Discriminant Analysis was performed in order to determine the subset of independent variables which best predicted the outcome of PFPS. All of the variables ($\Delta\rho_{max}$, $\Delta\psi_{max}$, F_{PFmax}, Q-angle, weekly) for each subject were analyzed using a Discriminant Analysis Function SPSS 5.0 (SPSS Inc., Chicago, Ill.). Final output for this analysis included a Discriminant Function (DF) equation and a percentage of correctly predicted outcomes. The DF equation only included the variables and their corresponding co-efficients which were significant predictors of PFPS. Any variable having a probability less than 0.05 was considered a significant predictor. In order to simplfy this analysis, the two injured groups (PFPS and Past-PFPS) were pooled together. The total number of subjects used was n =20 for the Asymptomatic group and n = 33 for the PFPS and Past-PFPS group. Two subjects were excluded from the latter group due to missing data.

3.4.4 Data Interpretation

3.4.4.1 Group Analysis

The groupings allowed the following speculations to be made concerning each analyzed variable, V_j(Group):

1. If V_j(PFPS) $=V_j$(Past-PFPS) $=$ V_j(AS), then no difference was present for the variable analyzed and this variable was assumed not to be associated with PFPS.

2. If V_j(PFPS) $=$ V_j(Past-PFPS) $\neq$ V_j(AS), then one can argue that there has been no change in the biomechanics due to patellofemoral pain and the variable is associated with PFPS.

3. If V_j(Past-PFPS) $=$ V_j(AS) $\neq$ V_j(PFPS), then the PFPS group may actually be changing their biomechanics to accommodate for their pain, or the former PFPS-group may have adapted a new style to accommodate for their pain that is similar to the healthy running style.

4. If V_j(PFPS) $\neq$ V_j(Past-PFPS) $\neq$ V_j(AS), then all three groups have distinct running styles. One way to interpret this potential result is that the group with pain has accommodated their running style because of the pain they are feeling, the group with former pain has accommodated their running style and is now running pain free, and the healthy group has its own distinct running style for the variable of interest.

5. If V_j(PFPS) $=$ V_j(AS) $\neq$ V_j(Past-PFPS), then the former PFPS-group has changed their running style to accommodate for the pain. The

asymptomatic group still may have the potential for achieving PFPS status, since their style is similar to the PFPS-group.

3.4.4.2 Individual Subject Analysis

Since it is believed that PFPS is a multifactorial problem, it may have been likely that the whole group would not react in a similar way for a given variable. The difference in averages of each variable across groups is not expected to be very high. For example, some subjects may have PFPS because of an extreme value for Q-angle and some subjects may have PFPS because of an extreme value for maximal tibial rotation with respect to the foot. Individual subject analysis allows for looking at extreme high or low values for each variable and for each subject. The method used in the present study was to look at individual subject differences in terms of differences from a mean value. All individual subject comparisons were done with respect to the average of the asymptomatic group. The average for the asymptomatic group provided a baseline of "normal" values for the variables measured in a group of recreational runners. Analysis included looking at the number of people above the average of the asymptomatic group.

4. Results

All of the results in the following text will be presented as a mean ± standard error of the measurement. All subjects ran with a natural heel-toe running pattern during the kinematic and kinetic data collection procedure.

4.1 Subject Demographics

Table 4.1: Subject Data for Five Variables Comparing Across Three Groups (mean ± S.E.)

Variable \ Grouping	AS (n=20)	PFPS (n=20)	Past-PFPS (n=15)
height (cm)	176.5 ± 2.1	170.0 ± 2.1	171.5 ± 3.3
mass (kg)	70.8 ± 3.0	66.8 ± 2.8	65.0 ± 3.5
age (years)	34.4 ± 2.3	34.6 ± 2.2	37.3 ± 2.2
# males	15	10	8
# females	5	12	7

No apparent differences were seen in any of the demographic variables. The split of males to females per group seems quite consistent except for the asymptomatic group where there were considerably more males. Gender was not used as a control in this study as there was no evidence that the incidence of PFPS for runners was greater for either gender.

4.2 Reliability Measurements

All measurements tested were considered to be reliable measures (Table 4.2). A benchmark value for Chronbach's Alpha (α_{chon}) of 0.85 was used for comparison. Any value less than this benchmark value rendered the variable as an unreliable measurement.

Table 4.2: Reliability Measurements Using Chronbach's Alpha Coefficient (α_{chron})

Variable \ Probability	α_{chron}
$\Delta\rho_{max}$	0.94
$\Delta\psi_{max}$	0.93
F_{PFmax}	0.96
Q-angle	0.95

4.3 Analysis of Variance

Averages, comparing across the three groups, for all variables measured are presented in Table 4.3. The first three variables in this table represent the *dynamic* variables, the fourth represents an *anatomical* variable and the last one represents a *training* variable. Analysis of Variance results are presented throughout the text. Individual results are presented in Tables A1 to A3 found in the Appendix.

Table 4.3: Group Comparisons for Dynamic, Anthropometric and Training Variables (mean $\pm$ S.E., with the number of subjects/variable presented in parentheses)

Grouping/ Variable	AS (n)	PFPS (n)	Past-PFPS (n)
$\Delta\rho_{max}$ [^{0}]	11.3 $\pm$ 0.9 (20)	11.6 $\pm$ 1.3 (17)	10.7 $\pm$ 1.6 (12)
$\Delta\psi_{max}$ [^{0}]	15.0 $\pm$ 1.1 (20)	17.4 $\pm$ 1.4 (19)	17.0 $\pm$ 1.7 (14)
F_{PFmax} [N]	4338 $\pm$ 552 (19)	4374 $\pm$ 321 (19)	3815 $\pm$ 510 (14)
Q-angle [^{0}]	12.7 $\pm$ 0.9 (20)	14.6 $\pm$ 0.8 (20)	13.1 $\pm$ 1.4 (15)
weekly [km]	43.8 $\pm$ 4.4 (20)	33.9 $\pm$ 3.3 (20)	39.9 $\pm$ 5.1 (15)

Comparisons of the asymptomatic values from this study to other studies is presented in Table 4.4. Values were not presented for weekly trianing distance as this study used a very specific group of recreational runners, and comparisons of this variable would not be reasonable.

Table 4.4: Comparison of Asymptomatic Values to Other Studies

Variable	Present Study	Other Study	Source
$\Delta\rho_{max}$ [^{0}]	11.3	21.8	Nigg and co-workers (1993)
$\Delta\psi_{max}$ [^{0}]	15.0	11.7	McClay (1990)
F_{PFmax} [N]	4338	3750	Scott and Winter (1990)
Q-angle [^{0}]	12.7	11.05	Messier and co-workers (1991)
weekly [km]	43.8	no comparison	no source

4.3.1 Maximal Tibial Rotation with Respect to the Foot ($\Delta\rho_{max}$)

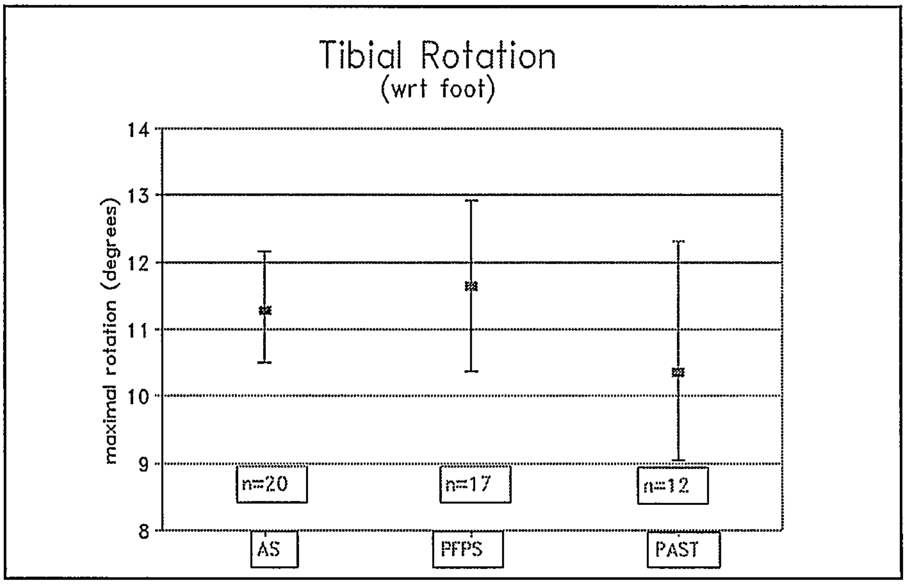

Figure 4.1: Maximal Tibial Rotation with Respect to the Foot ($\Delta\rho$max) for Heel-Toe Running Copmparing Across Three Groups

Maximal tibial rotation with respect to the foot did not significantly differ (F (2, 46) = 0.22, p = .806) across the three groups. The PFPS group had a slightly higher average (11.6 ± 1.3^0) maximal rotation compared to the asymptomatic group (11.3 ± 0.9^0) and the Past-PFPS group (10.7 ± 1.6^0) (Figure 4.1).

4.3.2 Maximal Tibial Rotation With Respect to the Femur ($\Delta\psi_{max}$)

Maximal tibial rotation with respect to the femur did not significantly differ (F (2, 50) = 1.04, p = .361) across the three groups. However, there was a trend of a

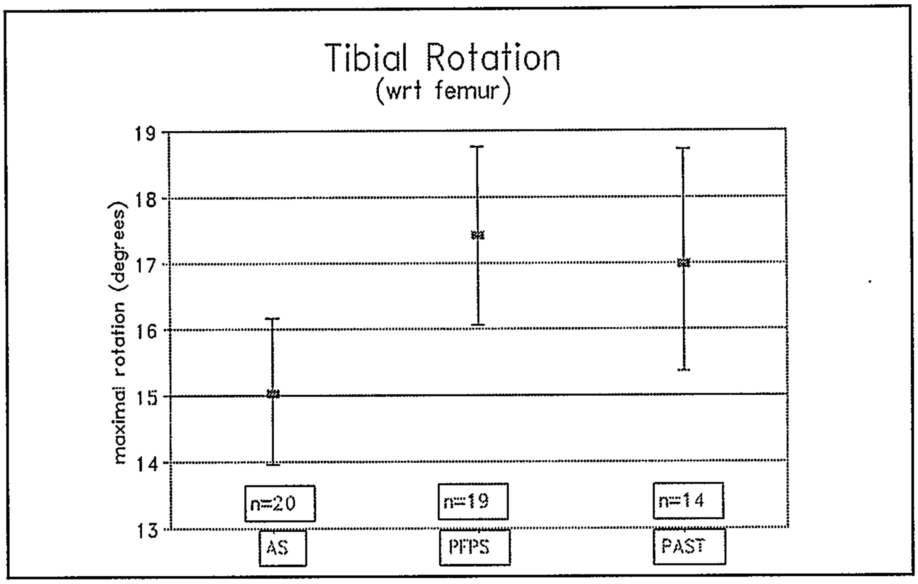

Figure 4.2: Maximal Tibial Rotation with respect to the Femur ($\Delta\psi max$) for Heel-Toe Running Comparing Across Three Groups

larger maximal tibial rotation for the PFPS (17.4 ± 1.4^0) and for the Past-PFPS group (17.0 ± 1.7^0) compared to the asymptomatic group (15.0 ± 1.1^0) (Figure 4.2).

4.3.3 Maximal Patellofemoral Joint Contact Force (F_{PFmax})

Comparison of F_{PFmax} across groups revealed that the Past-PFPS group (3815 ± 510 N) had a lower value than the asymptomatic (4338 ± 552 N) and the PFPS group (4374 ± 321 N) (Figure 4.3). This difference was not statistically significant (F (2, 49) = 0.42, p = .659).

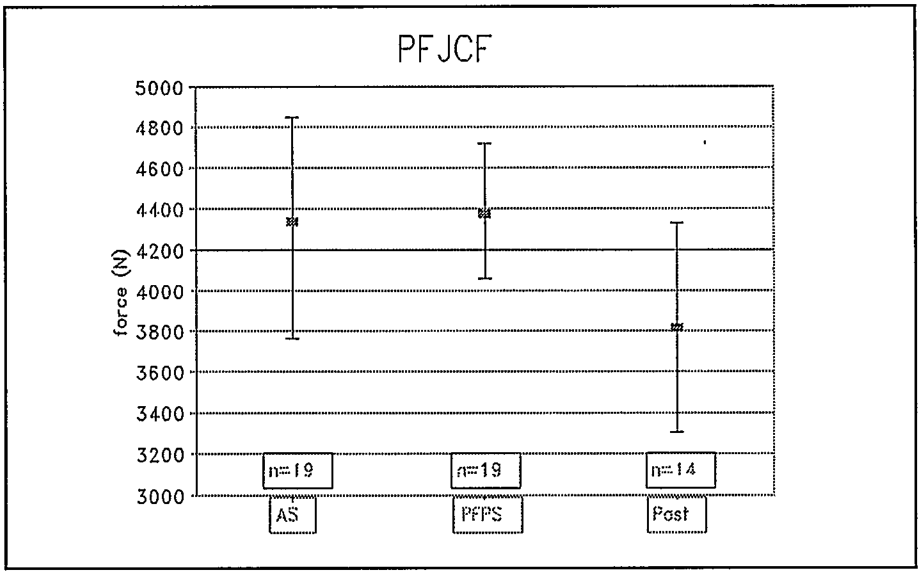

Figure 4.3: Maximal Patellofemoral Joint Contact Force (F_{PFmax}) for Heel-Toe Running Comparing Across Three Groups

4.3.4 Quadriceps-angle (Q-angle)

Q-angle (Figure 4.4) for both the PFPS (14.6 ± 0.8^0) and the Past-PFPS

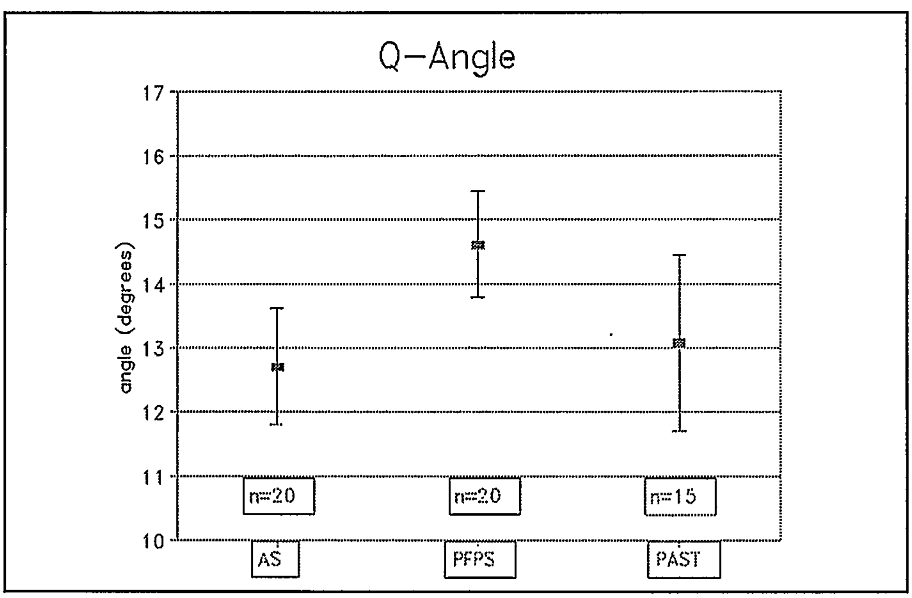

Figure 4.4: Quadriceps Angle Comparing Across Three Groups

(13.1 ± 1.4^0) were slightly larger than the asymptomatic group (12.7 ± 0.9^0). There were no statistical differences among the three groups ($F\ (2, 52) = 1.14$, $p = .329$).

4.4 Discriminant Function Analysis

The Discriminant Analysis showed that only one variable, maximal tibial rotation with respect to the femur ($\Delta\psi_{max}$), was a significant ($\alpha = 0.05$) predictor of the outcome of PFPS. The Discriminant Function (DF) generated was:

$$DF = -3.13 + 1.86(\Delta\psi_{max})$$

The DF values for the group means were:

$$DF_{AS} = -.356$$

$$DF_{PFPS} = .242$$

Using this equation, the percent of grouped cases that were correctly classified was 54.72 % of all of the cases. Predictions were properly classified for 12 of 20 in the Asymptomatic group and 17 of 33 in the PFPS group. The positive value for the DF_{PFPS} means that if a higher value for $\Delta\psi_{max}$ was observed, then it would belong to the PFPS group.

4.5 Training Variables

Training related variables have been compiled and presented in Table 4.4.

The distances presented in the table represent the distances run before injury for the injured groups and the current distance for the asymptomatic group. Percentage (%) cut-back was a variable only applicable to the injured groups and was presented as an average decrease to weekly running distance because of pain.

Table 4.5: Training Related Variables Comparing Across Groups (mean ± S.E.)

Grouping/ Variable	AS (n=20)	PFPS (n=20)	Past-PFPS (n=15)
Daily Distance (km)	9.2 ± 0.5	8.8 ± 0.5	9.6 ± 0.9
Weekly Distance (km)	43.8 ± 4.4	33.9 ± 3.3	39.9 ± 5.1
Years Run (years)	10.6 ± 2.0	9.8 ± 2.3	8.6 ± 1.9
% cut-back (% of weekly)	nil	57.4 ± 8.7	52.4 ± 10.5

Training related variables were consistent between groups. Since weekly running distance has been statistically related to running injuries (van Mechelen, 1992), a one-way ANOVA was performed on the weekly runnning distance to determine if any differences between groups could be observed. No statistical difference ($F(2, 52) = 1.51$, $p = .231$) was seen among the three groups for weekly running distance. The range of weekly running distances for all three groups were between 10-90 km with an average of 39.13 ± 2.46 km. Both injured groups reported to have decreased their regular weekly running distance by over 50% when their pain was at its worst.

4.6 Individual Subject Differences

Figures 4.5 and 4.6 represent individual differences for the PFPS group for the dynamic,

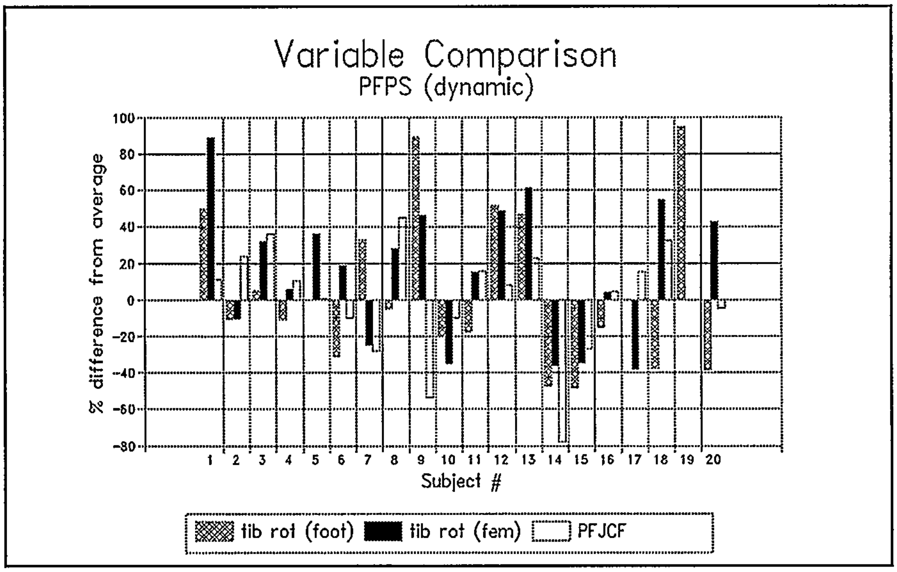

Figure 4.5: Individual Subject Differences for the PFPS group Presented as a % Difference from the Average of the Asymptomatic Group (Dynamic Variables)

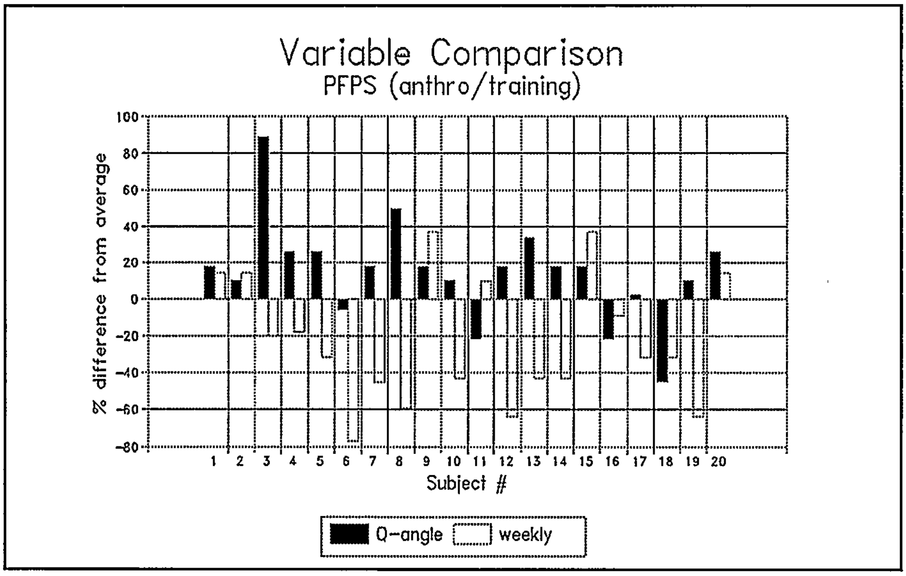

Figure 4.6: Individual Subject Differences for the PFPS group Presented as a % Difference from the Average of the Asymptomatic Group (Anthropometric and Training Variables)

anthropometric and training variables. Figures 4.7 and 4.8 represent individual differences for the Past-PFPS group for the dynamic, anthropometric and training variables. The values presented by the bar graphs are % differences from the average of the asymptomatic group for each subject. For example, subject #1 (PFPS group) had higher than average values for all of the variables $\Delta\rho_{max}$, $\Delta\psi_{max}$, F_{PFmax}, (Figure 4.5) Q-angle and weekly running distance (Figure 4.6). On

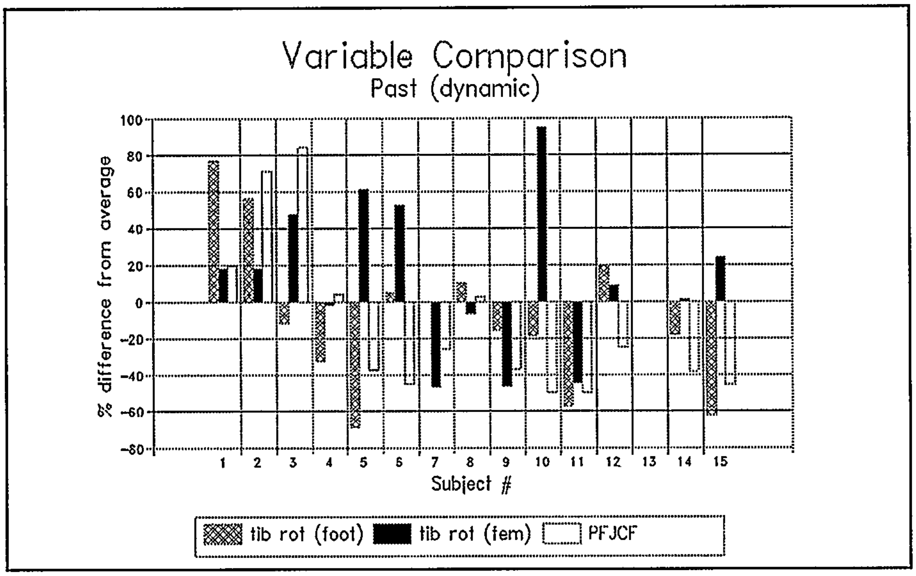

Figure 4.7:Individual Subject Differences for the Past-PFPS group Presented as a % Difference from the Average of the Asymptomatic Group (Dynamic Variables)

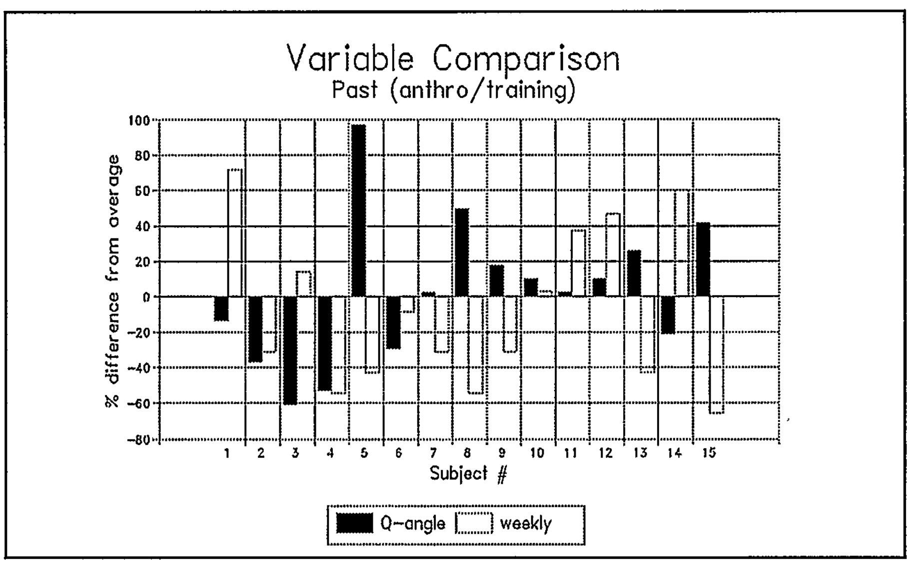

Figure 4.8:Individual Subject Differences for the Past-PFPS group Presented as a % Difference from the Average of the Asymptomatic Group (Anthropometric and Training Variables)

the other hand subject #2 (PFPS group) had higher than average values for the dynamic variable F_{PFmax} (Figure 4.5), the anthropometric variables Q-angle and training variable weekly running distance (Figure 4.6).

5. Discussion

This study was performed to detect whether specific functional biomechanical, anthropometric or training variables were different for runners with and without PFPS. It was hypothesized that maximal tibial rotation with respect to the foot ($\Delta\rho_{max}$), maximal tibial rotation with respect to the femur ($\Delta\psi_{max}$), maximal patellofemoral joint contact force (F_{PFmax}) and the Q-angle were larger for runners with PFPS than for the asymptomatic runners. The following discussion will probe into this question with a focus on each of the variables measured.

5.1 Group Differences

During running, it has been documented that the tibia internally rotates with respect to the foot from touchdown of the foot until approximately 50% stance after which it rotates externally until push-off (Nigg et al., 1993). Changes in contact patterns within the patellofemoral joint have been shown in live subjects at varying knee flexion angles (Ronsky, 1994). Changes in pressures in the patellofemoral joint have also been shown for varying degrees of knee flexion angles (Hehne et al., 1982, Buff et al., 1988). During running, the patella has been shown to shift medially with respect to the femur (McClay, 1990). It may be speculated that excessive internal tibial rotation may cause the patella to move medially thus changing the contact area.

This may change the pressure magnitude and/or change the location of the contact area to an area not usually loaded during normal daily activities. The pain felt in the anterior of the knee may be pain in the subchondral bone due to this change in contact area.

A common thought in the biomechanics research community is that if a subject is feeling pain in their lower limb, the biomechanics of their running style may change. One explanation for this change may be that the subject is attempting to minimize the pain by changing their running style. If a comparison between an injured subject and an uninjured subject is done, and this comparison reveals a difference in certain biomechanical parameters, would this be a true difference or would this difference be because of the pain? There were no statistical differences seen in any of the variables between the PFPS and the Past-PFPS groups. This suggests that the presence or absence of pain has not significantly and consistently changed the biomechanics of running to accomodate the pain.

Asymptomatic group values for the variables tested in this study were similar for two of the variables, maximal patellofemoral joint contact force (F_{PFmax}) and Q-angle, but not similar for maximal tibial rotation with respect to the foot ($\Delta\rho_{max}$) or maximal tibial rotation with respect to the femur ($\Delta\psi_{max}$) (see Table 4.4). Marker placement on the foot in this present study was only on the rearfoot, whereas Nigg and co-workers had a marker placement set-up on the whole foot. This may have been the reason for the discrepancy between the two results. Maximal tibial rotation with respect to the femur was greater for this study compared to values from McClay (1990). McClay (1990) used an intercortical bon-pin method to measure this movement, where the present study used an external skin marker method. The shapes of the curves for all of the kinematic variables in the present study did match the shape of the kinematics from previous studies for heel-toe running. Typical motions of the tibia with respect to the femur and with respect to the foot include an internal rotation until approximately 50 % of stance, followed by an external rotation until push-off (McClay, 1990, Nigg et al., 1993).

Only small differences (0.3^0) were seen between the Asymptomatic and PFPS groups for **maximal lower leg rotation with respect to the foot ($\Delta\rho_{max}$).** However, the standard error (Table 4.4) for the PFPS group was higher than that of the Asymptomatic group. This indicates that individual subjects in the PFPS group have more extreme high or low values. It does not appear from the present results that an increase in rotation of the lower leg with respect to the foot is a dominant factor in the onset of PFPS. Some subjects with PFPS have a high maximal tibial rotation with respect to the foot. However, some subjects with no pain have a high maximal tibial rotation with respect to the foot as well. Consequently, a high maximal tibial rotation with respect to the foot is not a necessary, but only a possible factor in the etiology of PFPS. The maximal tibial rotation with respect to the foot is, however, not the variable which can functionally explain the development of PFPS. It is only chosen because the results of this variable measured with the skin markers are close to the results of the bone markers (Reinschmidt, submitted). The functionally appropriate variable, maximal tibial rotation with respect to the femur, will be discussed in the following paragraph.

Maximal tibial rotation with respect to the femur ($\Delta\psi_{max}$) attempts to quantify relative motion of the tibia with respect to the femur. Average values for the PFPS and Past-PFPS groups were quite similar. Even though there were no significant differences between the PFPS and Asymptomatic groups, there was a trend for a higher maximal rotation (approximately 15% higher) for the PFPS if compared to the Asymptomatic group. The tendency of the PFPS group to rotate their tibia with respect to the femur more is interpreted as one possible mechanism associated with the onset of PFPS. The standard deviation was higher for the PFPS compared to the Asymptomatic group. This indicates that individual subjects in the PFPS group may have extremely high values for $\Delta\psi_{max}$ compared to the Asymptomatic group. For example, the two highest average values for tibial rotation with respect to the femur for the PFPS group were 28.4^0 and 24.2^0 for the Asymptomatic group the two highest values were 25.8^0 and 21.7^0.

Many efforts have been made in the past to estimate forces in the patellofemoral joint during isometric knee extension motions (Macdonald et al., 1989) and during actual running (Scott and Winter, 1990). A sagittal plane model of the patellofemoral joint, adapted with changes from Scott and Winter (1990), was used to estimate joint contact forces. The Past-PFPS grouped tended to have lower (15 % lower) $\mathbf{F}_{\mathbf{PFmax}}$ compared to the PFPS group. One way to explain this trend would be that the Past-PFPS group has changed their running style in order to lower their F_{PFmax}. If this is indeed true, then it can be speculated that this pain source can be reduced by gait adaptations. According to the model used in this study to calculate F_{PFmax}, this lower value may have been due to a reduction in one of the input variables, knee moment or knee flexion angle. A larger value for both of these variables would have yielded a larger F_{PFmax}. Each of the input variables may have been contributing individually, and adding the effects of all of them may have been confounding. It is difficult to assess whether it may have been knee moment and/or knee flexion angle which was contributing to a lower F_{PFmax} for the Past-PFPS group since these variables have not been quantified.

The **Q-angle** has been proposed as a discriminator for the likelihood of developing PFPS (Messier et al., 1991). However, it has also been proposed that there is no difference in the Q-angle for people with and without PFPS (Caylor et al., 1993). The results of the present study showed no differences in the Q-angle for subjects with and without PFPS. Although the PFPS and the Past-PFPS groups showed a trend towards slightly larger Q-angle values (approximately 10 % larger), no statistical difference was detected. One reason for a slightly smaller Q-angle value in the Asymptomatic group may have been because there was a higher proportion of males to females in this group. Separation of the males and females in this group revealed that the males had a smaller Q-angle (12.3 ± 3.8^0, n = 15) compared to the females (13.8 ± 4.5^0, n = 5). It has been stated that males have smaller Q-angles (Roy and Irvin, 1983) and the results may have been closer if there were more females in this group. Messier and co-workers (1991) reported Q-angle values of 11.05 ± 0.36^0 and 17.19 ± 0.60^0 for runners without and with PFPS, respectivley. Caylor and co-workers (1993) report values of 12.4 ± 5.1^0 and 11.1 ± 5.5^0 for the asymptomatic and PFPS groups, respectively. The reason for the discrepancy in the results between our study and the study by Messier and co-workers (1991) is not obvious. One possible explanation may be that the Q-angle has been measured differently in the two studies. However, this can not be verified since the information about the measurement protocol is missing in the Messier study.

An increase in **weekly running distance** has been a factor that has been statistically associated with running injuries (van Mechelen, 1992). A proposed mechanism responsible for the onset of PFPS is chronic overload of the tissues in the patellofemoral joint, due to repetitive loading, causing tissue degeneration and ultimately bone pain. The present study showed no statistical differences across groups. The PFPS and the Past-PFPS groups tended to have an approximately 20 % lower weekly distance compared to the Asymptomatic group. This study focussed on the analysis of recreational runners. For higher level athletes, over-trianing may be a problem when it comes to running injuries. Running distance, for the group of recreational runners tested in this study, may not have been a factor itself, because the distance was not high enough to cause injury. Instead, it can be thought that the other biomechanical factors work in combination with the weekly training distance to explain the onset of PFPS.

The Stepwise Discriminant Function Analysis revealed that maximal rotation of the tibia with respect to the femur ($\Delta\psi_{max}$) was the only variable to have predictive power to detect the outcome of PFPS. The prediction of 54.72 % of all cases is small and may have no merit. However, the trend of $\Delta\psi_{max}$ to be higher for the PFPS group may be important when looking at individual subject differences.

Original sample size calculations prior to the study, using a maximal tibial rotation with respect to the femur as the value of interest, yielded a value of approximately n = 17 / group (average difference = 5^0; S.D. = $\pm 5^0$; $\alpha = 0.05$; $\beta = 0.10$). Power analysis (average difference = 2.4^0; S.D. = $\pm 5.4^0$; $\alpha = 0.05$; n = 20) after the study revealed a power of 40.5 %. This represented a 40.5 % chance of rejecting the null hypothesis, when the null hypothesis was false. This low power can be attributed to the low average difference between the groups. A sample size calculation, using the above information and a power of 90 %, revealed in order to see a difference between the groups we would require approximately 54 subjects / group. This is not an unrealistic number and the data from this study could be used as pilot data for a future study which would have more subjects per group.

The identification of causal factors for the development of sport injuries is a difficult task. The task is increasingly more difficult when several compounding variables are involved. In the case of this study, PFPS is already a not well defined pathology. Additionally, there are most likely several factors that may play a role in the development of PFPS. This study concentrated on some factors for which possible injury mechanisms were available. These factors included, the Q-angle, the tibial rotation, the force between the patella and the femur and the weekly running distance. From those variables, none showed significant group differences. Tibial rotation with respect to the femur, the variable describing the relative axial rotation of the tibia with respect to the femur, showed some predictive power in the discriminant analysis. This result suggests that the variable, which was hypothesized to be important for the development of PFPS, may be an important factor. The fact that the influence is not strong may be because of one of two reasons. Firstly, there is a problem in the accuracy for measuring maximal tibial rotation with repsect to the femur which introduces an error that affects the actual strong influence of this variable on the development of PFPS, or secondly, there may only be a weak influence of the axial tibio-femoral rotation on the development of PFPS. It is speculated by the author that a combination of several factors plays a role in the development of PFPS and that a thorough subject by subject analysis may provide more insight into possible mechanisms and will be discussed in the following section.

5.2 Individual Subject Differences

PFPS in runners is assumed to be a multi-factorial problem combining the effects of biomechanical, anthropometric and training variables. Some subjects may have PFPS because they have a large Q-angle, while other subjects may have PFPS because of a high tibial rotation and a high Q-angle. Figures 5.1 and 5.2 present data on the number of subjects in the PFPS group above the average of the asymptomatic group for one or a combination of several factors possibly responsible for the development of PFPS. These two figures present only some possible combinations of the factors that we can look at. The factors presented in these two figures were chosen because it is believed that they can explain the functional reasons of PFPS the best.

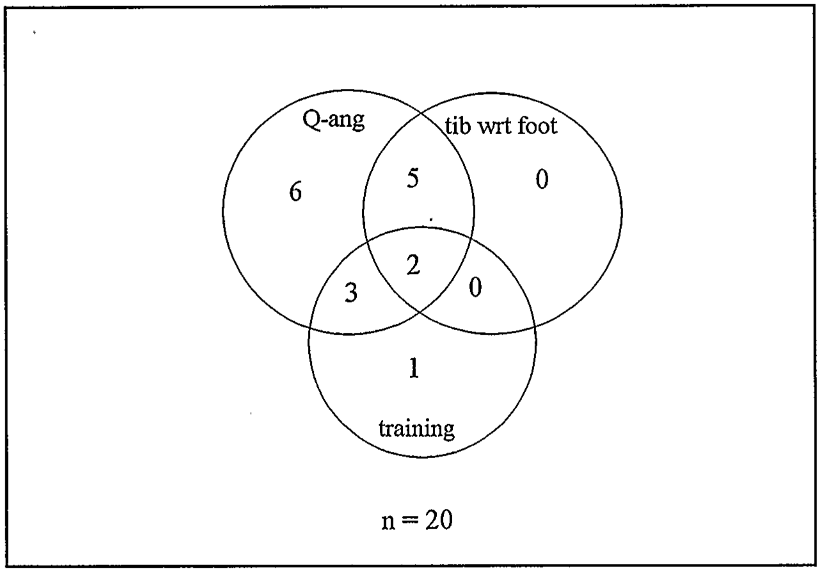

Figure 5.1: Number of Subjects (PFPS Group) for Three Variables (Q-angle, tibial rotation with respect to the foot, weekly running distance) Higher than the Average of the Asymptomatic Group.

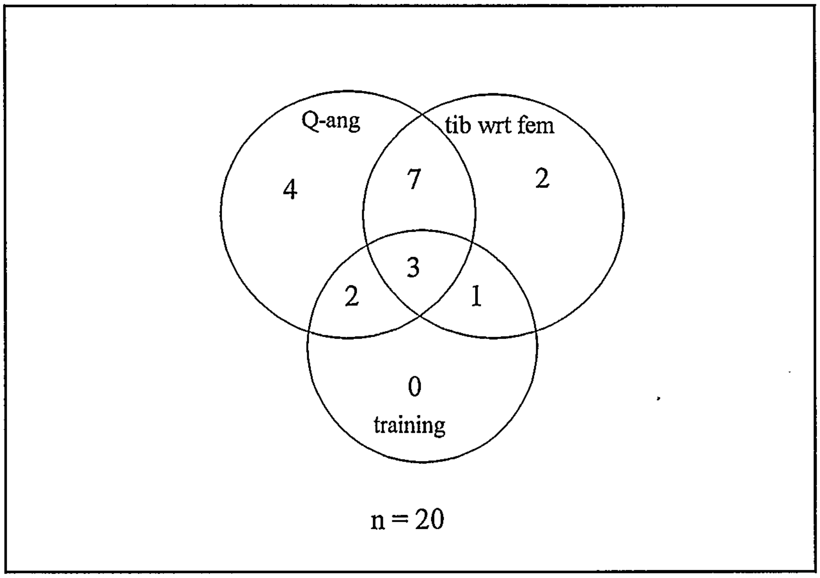

Figure 5.2: Number of Subjects (PFPS Group) for Three Variables (Q-angle, tibial rotation with respect to the femur, weekly running distance) Higher than the Average of the Asymptomatic Group

Figure 5.1 presents data on the three variables Q-angle, maximal tibial rotation with respect to the foot, and weekly training distance. The numbers in Figure 5.1, where the circles do not overlap (6 = Q-angle, 0 = tibial rotation with respect to the foot, 1 = weekly training distance) represent the number of subjects that have higher than average values for only that variable. The overlapped numbers represent subjects that have higher than average values for a combination of variables. Adding all of the numbers within one circle (e.g., total Q-angle = 6 + 5 + 2 + 3 = 16) represents the total number of subjects that have a higher than average Q-angle compared to the mean of the asymptomatic group.

Figure 5.2 presents data for the three variables Q-angle, tibial rotation with repsect to the femur and weekly training distance. The results of Figure 5.2 are closest to a functional explanation of the etiology of PFPS. The following discussion concentrates, consequently on this figure. Nineteen of the 20 subjects with PFPS showed, in at least one of the three variables, values which were higher than the corresponding mean of the Asymptomatic group. From these 19, only 6 had high values in only one variable (zero for training variables), 10 in 2 variables and 3 in all three variables. The most frequent combination was a high Q-angle with a high tibio-femoral rotation. This may be an indication that a combination of high values in these two factors may be a good predictor of potential development of PFPS. However, a considerably larger number of males in the Asymptomatic group may have lead to a lower average value for Q-angle. This could have lead to an overestimation of the number of subjects with PFPS above what was considered a "normal" Q-angle.

6. Conclusions

Patellofemoral Pain Syndrome (PFPS) is a common problem for regular, recreational runners. The etiology of PFPS within a running population is not well understood. Several factors have been proposed to be associated with the development of PFPS. However, the actual etiology is still not well understood.

Patellar malalignment, causing abnormal joint contact has been proposed as a mechanism leading to the onset of PFPS. This study was aimed at analyzing functional (anatomical and dynamic) and training variables that may be associated with PFPS in runners. The primary objective was to study the functional variables of internal rotation of the tibia with respect to the foot ($\Delta\psi_{max}$), internal rotation of the tibia with respect to the femur ($\Delta\gamma_{max}$), patellofemoral joint contact force (F_{PFmax}), Q-angle and weekly training distance in three groups including an asymptomatic group (never had PFPS), a PFPS group (feeling patellofemoral pain while running), and a Past-PFPS group (have had patellofemoral pain in the past, but not feeling pain now). The third group (Past-PFPS) was added to the study to control for any chances that pain may be causing changes in biomechanics. The methods used included firstly administration of a questionnaire to assess past running injuries and runner history, secondly anthropometric measurements of the lower limb, and finally a full kinematic and kinetic running analysis. It was speculated that extremely high values for these functional variables may cause a change in the contact/pressure patterns in the patellofemoral joint to a point exceeding physiological limits. The pain felt in the patellofemoral joint was speculated to be subchondral bone pain and was not due to patellar tendinitis, quadriceps tendinitis, peripatellar tendinitis or prepatellar bursitis.

It was hypothesized that runners with PFPS had a larger maximal internal rotation of the lower leg while running. A larger internal rotation may be associated with a larger medial excursion of the patella, leading to a change in the contact/pressure pattern within the patellofemoral joint to regions not usually loaded during normal daily activities. Maximal rotation of the lower leg with respect to the foot or with respect to the femur were not statistically associated to PFPS. Both the PFPS and Past-PFPS group had higher values for maximal tibial rotation with respect to the femur, however, these differences were not statistically significant.

A theoretical estimate of the patellofemoral joint contact force revealed no differences among the three groups analyzed in this study. This estimate was done only in the sagittal plane using a model adapted, with changes, from a previous study (Scott and Winter, 1990). It has been recognized that this problem is one which is 3-dimensional in nature and a more complicated model than the one presented here may be required in order to more properly assess the situation. A 3-dimensional model may be able to take into account abduction-adduction, internal-external and flexion-extension moments and motions to more accurately estimate the patellofemoral joint contact force.

There is no agreement in the literature as to whether or not an excessive Q-angle is related to the occurance of PFPS. Some studies have shown no differences in Q-angle between subjects with and without PFPS (Caylor et al., 1993), while other studies have shown Q-angle to be different (Messier et al., 1991). Slightly higher values for Q-angle (10 % higher) were measured in this study for subjects with PFPS, however, the differences were statistically not different. For this group of recreational runners, Q-angle was not a factor associated with PFPS.

A Stepwise Discriminant Function Analysis revealed that maximal tibial rotation with repsect to the femur ($\Delta\psi_{max}$) was the only factor that was a possible predictor to classify PFPS. The Discriminant Function was able to properly predict 54.72 % of all of the cases, which was considered a low prediction percentage. All of the other variables were considered as poor predictors of PFPS.

In summary, there were no group differences for the factors of maximal tibial rotation with respect to the foot, maximal tibial rotation with respect to the femur, maximal patellofemoral joint contact force, Q-angle and weekly training distance between groups with and without PFPS. However, it is believed that PFPS is a multi-factorial problem in which several factors play a role in the development of PFPS. This study only concentrated on some factors for which good mechanical reasons were available. The variable that had the closest functional explanation to etiology of PFPS, maximal tibial rotation with respect to the femur, was the only variable to show some predictive power. This suggests that this variable may be an important factor in the development of PFPS. Individual subject analyses revealed that a combination of both Q-angle and maximal tibial rotation with respect to the femur, together, may be good predictors of PFPS. Future studies using tibial rotation as a variable related to the onset of PFPS in a running population, should use larger sample sizes if group differences are to be seen.

References

Alexander, R. and Vernon, A. (1975) The dimemsions of the knee and ankle muscles and the forces they exert. *Journal of Human Movement Studies* ***1***, 115-123.

Bahlsen, A. (1988) The etiology of running injuries. *Ph.D. Thesis, University of Calgary, 1988.*

Bovens, A.M.P., Janssen, G.M.E., Vermeer, H.G.W., Hoeberigs, J.H. and Janssen, M.P.E. (1989) Occurrance of running injuries in adults following a supervised trianing program. *International Journal of Sports Medicine* ***10***, S186-S190.

Buczek, F.L. and Cavanagh, P.R. (1990) Stance phase knee and ankle kinematics and kinetics during level running. *Medicine and Science in Sports and Exercise* ***22(5)***, 669-677.

Buff H., Jones, L.C., Hungerford and D.S. (1988) Experimental determination of forces transmitted through the patellofemoral joint. *Journal of Biomechanics* ***21(1)***, 17-23.

Callaghan, M.J. and Baltzopoulos, V. (1992) Anterior knee pain: the need for objective measurement *Clinical Biomechanics* *7*, 67-74.

Callaghan, M.J. and Baltzopoulos, V. (1994) Gait analysis in patients with anterior knee pain. *Clinical Biomechanics* ***9***, 79-84.

Caylor, D. and Fites, R. (1993) The relationship between quadriceps angle and anterior knee pain syndrome. *Journal of Orthopaedic Sports and Physical Therapy* ***17(1)***, 11-16

Clement, D.B., Taunton, J.E., Smart, G.W. and McNicol, K.L. (1981) A survey of overuse running injuries. *The Physician and Sportsmedicine* ***9(5)***, 47-58.

D'Amico, J.C. and Rubin, M. (1986) The influence of foot orthoses on Q-angle. *Journal of the American Podiatric Medical Association.* ***76(6)***, 337-340

DeVita, P. and Dawson, M.L. (1992) A biomechanical analysis of patellofemoral stress syndrome. *Journal of Athletic Training* ***27(1)***, 64-69.

Dillon, P.Z., Updyke,W.N. and Allen, W.C. (1983) Gait analysis with reference to chondromalacia patellae. *The Journal of Orthopaedic and Sports Physical*

Therapy ***5(3)***, 127-131.

Eichner, E.R. (1989) Does running cause osteoarthritis? *The Physician and Sports Medicine* ***17(3)***, 147-154.

van Eijden, T.M.G.J., Boer, W. and Weijis, W.A. (1985) The orientation of the distal part of the quadriceps femoris muscle as a function of the knee flexion-extension angle. *Journal of Biomechanics* ***18(10)***, 803-809.

van Eijden, T.M.G.J., Kouwenhoven, E., Verberg, J. and Weijs, W.A. (1986) A mathematical model of the patellofemoral joint. *Journal of Biomechanics* ***19(3)***, 219-229.

van Eijden, T.M.G.J., Weijs, W.A., Kouwenhoven, E. and Verberg,J. (1987) Forces acting on the patella during maximal voluntary contraction of the quadriceps at different knee flexion and extention angles. *Acta Ant.* ***127***, 310-314.

Eng, J.J. and Pierrynowski, M.R. (1993) Evaluation of soft foot orthotics in the treatment of patellofemoral pain syndrome. *Physical Therapy* ***73(2)***, 62-70.

Finestone, A., Radin, E.L., Lev, B., Shlamkovitch, N., Weiner, M. and Milgrom,C. (1993) Treatment of overuse patellofemoral pain: Prospective randomized controlled clinical trial in a military setting. *Clinical Orthopaedics and Related Research* ***293***, 208-210.

Fulkerson, J.P. and Hungerford, D.S. (1990) *Disorders of the Patellofemoral Joint*, 2nd Edition, Williams and Wilkins, Baltimore.

Gaffney, K., Fricker, P., Dwyer, T., Barrett, E., Skibinski, K. and Coutts, R. (1992) Patellofemoral joint pain: A comparison of two treatment programs. *Excel* ***8***, 179-189.

Goodfellow, J., Hungerford, D.S. and Woods, C. (1976) Patellofemoral joint mechanics and pathology(2). *The Journal of Bone and Joint Surgery* ***58B(3)***, 291-299.

Grana, W.A. and Coniglione, T.C. (1985) Knee disorders in Runners. *The Physician and Sportsmedicine* ***13(5)***, 127-133.

Grood, E.S. and Suntay, W.J. (1983) A joint coordinate system for the clinical description of three dimensional motions: application to the knee. *Journal of Biomechanical Engineering* ***105***, 136-144.

Hebert, L.J., Gravel, D., Arsenault, A.B. and Trembley, G. (1994) Patellofemoral pain syndrome: the possible role of an inadequate neuromuscular mechanism. *Clinical Biomechanics* ***9***, 93-97.

Hefzy, M.S., Jackson, W.T., Saddemi, S.R. and Hsieh,Y.F. (1992) Effects of tibial rotations on patellar tracking and patellofemoral contact areas. *Journal of Biomedical Engineering* ***14***, 329-343.

Hehne, H.J., Heberland, H., Hultzsch, W. and Jantz, W. (1982) Measurements of two-dimensional pressure distribution and contact areas of a joint using a pressure sensitive foil. In: *Biomechanics: Principles and Applications* 197-203. Edited by Husikes, R., van Campen, D.H and de Wijn J.R., The Hague, Martinus Nijhoff Publishers.

Hintermann, B., Nigg, B.M., Sommer, C. and Cole, G.K. (1994) Transfer of movement between calcaneus and tibia in vitro. *Clinical Biomechanics* ***9***, 349-355.

Hirokawa, S. (1991) Three-dimensional mathematical model analysis of the patellofemoral joint. *Journal of Biomechanics* ***24(8)***, 659-671.

Huberti, H.H. and Hayes, W.C. (1984) Patellofemoral contact pressures. *The Journal of Bone and Joint Surgery* ***66A(5)***, 715-724.

Huberti, H.H., Hayes, W.C., Stone, J.C. and Shybut, G.T. (1984) Force ratios in the quadriceps tendon and ligamentum patellae. *Journal of Orthropaedic Research* ***2(1)***, 49-54.

Hungerford, D.S. and Barry, M. (1979) Biomechanics of the patellofemoral joint. *Clinical Orthopaedics and Related Research* ***144***, 9-15.

Jacobs, S.J. and Berson, B.L. (1986) Injuries to runners:a study of entrants to a 10,000 meter race. *The American Journal of Sports Medicine* ***14(2)***, 151-155.

Jacobson, K.E. and Flandry, F.C. (1989) Diagnosis of anterior knee pain. *Clinics in Sports Medicine* ***8(2)***, 179-195.

James, S.L., Bates, B.T. and Ostering, L.R. (1978) Injuries to runners. *The American Journal of Sports Medicine* ***6(2)***, 40-49.

Javadpour, S.M., Finegan, P.J. and O'Brien,M. (1991) The anatomy of the extensor mechanism and its clinical relevance. *Clinical Journal of Sports Medicine* ***1(4)***, 229-235.

van Kampen, A., Huiskes, R., Blankevoort, L. and van Rena, T.G.J. (1986) The three-dimensional tracking of the patella in the human knee joint. *32nd Annual ORS*, 386.

van Kampen, A. and Huiskes, R. (1990) The three-dimensional tracking pattern of the human patella. *Journal of Orthopaedic Research* ***8***, 372-382.

Kannus, P.A. and Niittymaki, S. (1994) Which factors predict the outcome in nonoperative treatment of patellofemoral pain syndrome? A prospective follow-up. *Medicine and Science in Sports and Exercise* ***26(3)***, 289-296.

Kernozek, T.W. and Greer, N.L. (1993) Quadriceps angle and rearfoot motion:relationships in walking. *Archives of Physical Medicine and Rehabilitation* ***74***, 407-410.

Konradsen, L., Hansen, E.L. and Sondergaard, L. (1990) Long distance running and osteoarthritis. *The American Journal of Sports Medicine* ***18(4)***, 379-381.

Koh, T.J., Grabiner, M.D. and de Stewart, R.J. (1992) In vivo tracking of the human patella. *Journal of Biomechanics* ***25(6)***, 637-643.

Lane, N.E., Bloch, D.A., Jones, H.H., Marshall, W.H., Wood, P. and Fries, J.F. (1986) Long distance running, bone density and osteoarthritis. *Journal of the American Medical Association* ***255(9)***, 1147-1151.

Lee, T.Q., Anzel, S.H., Bennett, K.A., Pang, D. and Kim, W.C. (1994) The influence of fixed rotational deformities of the femur on the patellofemoral contact pressures in the cadaver knee. *Clinical Orthopaedics and Related Research* ***302***, 69-74.

Lengsfeld, M., Ahlers, J. and Ritter, G. (1990) Kinematics of the patellofemoral joint. *Archives of Orthopaedic Trama and Surgery* ***109***, 280-283.

Macdonald, D.A., Hutton, J.F. and Kelly, I.G. (1989) Maximal isometric patellofemoral contact force in patients with anterior knee pain. *The Journal of Bone and Joint Surgery* ***71B(2)***, 296-299.

Macera, C.A., Russell, R.P., Powell, K.E., Jackson, K.L., Kendrick, J.S. and Craven, T (1989) Predicting lower-extremity injuries among habitual runners. *Archives of Internal Medicine* ***149***, 2565-2568.

Marti, B., Vader, J.P., Minder, C.E. and Abelin, T. (1988) On the epidemiology of running injuries. *The American Journal of Sports Medicine* ***16(3)***, 379-385.

Matheson, G.O., Macintyre, J.G., Taunton, J.E., Clement, D.B. and Lloyd-Smith,

R. (1989) Musculoskeletal injuries associated with physical activities in older adults. *Medicine and Science in Sports and Excercise* ***21(4)***, 379-385.

Matthews, L.S., Sonstegard, D.A. and Henke, J.A. (1977) Load bearing characteristics of the patellofemoral joint. *Acta Orthopedica Scanadinavia* ***48***, 511-516.

McArdle, W.D., Katch, F.I. and Katch, V.L. (1991) *Exercise Physiology: Energy, Nutrition and Human Performance, 3rd Ed.* Lea & Febiger, Malvern, PA.

McClay, I.S. (1990) A comparison of tibiofemoral and patellofemoral joint motion in runners with and without patellofemoral pain. *Ph.D. Thesis, The Pennsylvania State University*, 1-238.

van Mechelen, W. (1992) Running injuries: A review of the epidemiological literature. *Sports Medicine* ***14(5)***, 321-335.

Merchant, A.C. (1988) Classification of patellofemoral disorders. *Arthroscopy 4(4)*, 253-240.

Messier, S.P. and Pittala,K.A. (1988) Etiologic factors associated with selected running injuries. *Medicine and Science in Sports and Exercise* ***20(5)***, 501-505.

Messier, S.P., Davies,S.E., Curl, W.W., Lowery, R.B. and Pack, R.J. (1991) Etiologic factors associated with patellofemoral pain in runners. *Medicine and Science in Sports and Exercise* ***23(9)***, 1008-1015.

Mow, V.C., Setton, L.A. and Ratcliffe, A. (1990) Structure function relationships for articular cartilage and effects of joint instability and trauma on cartilage function, in Brant, K.D.(ed.): *Cartilage Changes in Osteoarthritis.* Indianapolis, IN, University of Indiana Press, 22-42.

Newell, S.G., and Bramwell, S.T. (1984) Overuse injuries to the knee in runners. *The Physician and Sports Medicine 12(3)*, 81-92.

Nigg, B.M., Cole, G.K. and Nachbauer, W. (1993) Effects of arch height of the foot on angular motion of the lower extremities in running. *Journal of Biomechanics* ***26(8)***, 909-916.

Nike (1989) Common running injuries. *Sport Research Review (March/April).*

Nisell R. and Ekholm, J. (1985) Patellar forces during knee extension. *Scandinavian Journal of Rehabilitation Medicine* ***17***, 63-74.

Nisell R. and Ericson, M. (1992) Patellar forces during iskinetic knee extension. *Clinical Biomechanics 7*, 104-108.

Panush, R.S., Schmidt, C., Caldwell, J.R., Edwards, N.L., Longley, S., Yonker, R., Webster, E., Nauman, J., Stork, J. and Pettersson, H. (1986) Is running associated with degenerative joint disease. *Journal of the American Medical Association **255(9)***, 1152-1154.

Radin, E.L., Yang, K.H., Riegger, C., Kish, V.L. and O'Conner, J.J. (1991) Relationship between lower limb dynamics and knee joint pain. *Journal of Orthopaedic Research **9***, 398-405.

Reilly, D.T. and Martens, M. (1972) Experimental analysis of the quadriceps muscle force and patellofemoral joint reaction force for various activities. *Acta Orthopedica Scandinavia **43***, 126-137.

Reinschmidt, C., van den Bogert, A.T., Nigg, B.M., Lundberg, A. and Murphy, N. Effect of skin movement artefact on the calculatin of knee joint motion during running. *(sumitted)*.

Ronsky, J (1994) In-vivo patellofemoral joint contact. *Ph.D. Thesis, The University of Calgary*, 1-287.

Roy, S. and Irvin, R. (1983) *Sports Medicine: Prevention, Evaluation, Management, and Rehabilitation,* Prentice-Hall, Englewood Cliffs, N.J., pp.317.

Sangeorzan, B.J. (1991) in:*Inman's Joints of the Ankle (2nd Edition)*. Williams & Wilkins, Baltimore, Maryland, pp. 65-73.

Scott, S.H. and Winter, D.A. (1990) Internal forces at chronic running injury sites. *Medicine and Science in Sports and Exercise **22(3)***, 357-369.

Simpson, K.J. and Bates, B.T. (1990) The effects of running speed on lower extremity joint moments generated during the support phase. *International Journal of Sport Biomechancis **6***, 309-324.

Spoor, C.W., van Leeuwen, J.L., Meskers, C.G.M., Titulaer, A.F. and Huson, A. (1990) Estimation of instantaneous moment arms of lower-leg muscles. *Journal of Biomechanics **23(12)***, 1247-1259.

Stephens, T. and Craig, C.L. (1990) The well being of Canadians. Highlights of the 1988 Campbell Survey. *Ottawa: Canadian Fitness and Lifestyle Research Insstitute.*

Steinkamp, L.A., Dillingham, M.F., Markel, M.D., Hill, J.A. and Kaufman, K.R. (1993) Biomechanical considerations on patellofemoral joint rehabilitation. *Journal of Sports Medicine* ***21(3)***, 436-444.

Townsend, P.R., Rose, R.M., Radin, E.L. and Raux, P. (1977) The biomechanics of the human patella and its implications for chondromalacia. *Journal of Biomechanics* ***10***, 403-407.

Vaughan, C.L. (1984) Biomechanics of running gait. *CRC Critical Reviews in Biomedical Engineering* ***12(1)***, 1-48.

Walter, S.D., Hart, L.E., Sutton, J.R., McIntosh, J.M. and Gauld, M. (1988) Training habits and injury experience in distance runners: age-and sex-related factors. *The Physician and Sportsmedicine* ***16(6)***, 101-113.

Walter, S.D., Hart, L.E., McIntosh, J.M. and Sutton, J.R. (1989) The Ontario cohort study of running-related injuries. *Archives of Internal Medicine* ***149***, 2561-2564.

Wickiewicz, T.L., Roy, R.R., Powell, P.L. and Edgerton, V.R. (1983) Muscle architecture of the human lower limb. *Clinical Orthopaedics and Related Research* ***179***, 275-283.

Winter, D.A. (1980) Overall principle of lower limb support during stance phase of gait. *Journal of Biomechanics* ***13***, 923-927.

Woodall, W. and Welsh, J. (1990) A biomechanical basis for rehabilitation programs involving the patellofemoral joint. *The Journal of Orthopaedic and Sports Physical Therapy* ***11(11)***, 535-542.

Zappala, F.G., Taffel, C.B. and Scuderi, G.R. (1992) Rehabilitation of patellofemoral joint disorders. *Orthopaedic Clinics of North America* ***23(4)***, 555-566.

Appendix

Table A1: Individual Subject Data for the **Asymptomatic Group**. Averages Are Presented for Three Trials for all Variables Except for Q-ang and Weekly Running Distance Where Only One Trial is Presented

var/ sub #	$\Delta\rho_{max}$ [^{0}]	$\Delta\psi_{max}$ [^{0}]	F_{PFmax} [N]	Q-ang [^{0}]	weekly [km]
1	13.9	18.2	4659	8	60
2	8.3	10.6	3774	18	60
3	15.3	12.9	2039	16	32
4	5.2	13.6	955	20	30
5	9.6	21.2	3378	7	30
6	9.8	10.3	7041	8	20
7	9.4	14.1	1614	9	30
8	6.2	10.0	4513	11	20
9	8.1	25.8	3548	14	50
10	12.9	12.4	8026	14	30
11	7.6	14.7	5417	14	24
12	13.6	21.7	7414	14	70
13	17.3	17.5	***	17	45
14	9.8	12.2	2571	10	45
15	8.8	12.8	4787	10	90
16	16.5	14.3	2041	8	80
17	11.7	6.8	2239	12	33
18	11.0	16.7	4477	10	50
19	18.4	18.2	9771	18	36
20	12.3	16.7	4157	16	40

Table A2: Individual Subject Data for the **PFPS Group**.. Averages Are Presented for Three Trials for All Variables Except for Q-ang and Weekly Running Distance Where Only One Trial is Presented.

var/ sub #	$\Delta\rho_{max}$ [^{0}]	$\Delta\psi_{max}$ [^{0}]	F_{PFmax} [N]	Q-ang [^{0}]	weekly [km]
1	16.9	28.4	4827	15	50
2	10.1	13.5	5385	14	50
3	11.9	19.8	5899	24	35
4	10.1	15.9	4802	16	36
5	***	20.4	4368	16	30
6	7.7	17.9	3915	12	10
7	***	11.3	3118	15	24
8	10.7	19.3	6275	19	18
9	21.3	22.0	2013	15	60
10	9.0	9.7	3915	14	25
11	9.3	17.4	5020	10	48
12	17.1	22.3	4691	15	16
13	16.5	24.2	5364	17	25
14	5.9	9.6	964	15	25
15	5.8	9.8	3166	15	60
16	9.6	15.6	4537	10	40
17	***	9.3	5011	13	30
18	7.0	23.3	5727	7	30
19	21.9	***	***	14	16
20	6.9	21.4	4153	16	50

Table A3: Individual Subject Data for the **Past-PFPS Group**. Averages Are Presented for Three Trials for All Variables Except for Q-ang and Weekly Running Distance Where Only One Trial is Presented.

var/ sub #	$\Delta\rho_{max}$ [^{0}]	$\Delta\psi_{max}$ [^{0}]	F_{PFmax} [N]	Q-ang [^{0}]	weekly [km]
1	20.0	17.8	5183	11	75
2	17.6	17.8	7414	8	30
3	10.0	22.2	7998	5	50
4	***	14.8	4509	6	20
5	3.6	24.2	2739	25	25
6	11.9	22.9	2399	9	40
7	***	8.1	3233	13	30
8	12.5	14.0	4466	19	20
9	9.5	8.1	2754	15	30
10	9.2	29.3	2183	14	45
11	4.8	8.4	2178	13	60
12	13.5	16.4	3278	14	64
13	***	***	***	16	25
14	9.3	15.3	2700	10	70
15	4.3	18.6	2375	18	15

Table A4: Individual Subject Differences for the **Asymptomatic Group** Presented as the Percentage Difference From the Average of the Asymptomatic Group.

var/ sub #	$\Delta\rho_{max}$ [%]	$\Delta\psi_{max}$ [%]	F_{PFmax} [%]	Q-ang [%]	weekly [%]
1	23	22	7	-37	37
2	-27	-29	-13	41	37
3	35	-14	-53	26	-27
4	-54	-10	-78	57	-31
5	-15	48	-22	-45	-31
6	-13	-31	62	-37	-54
7	-17	-6	-63	-29	-31
8	-45	-33	4	-13	-54
9	-28	71	-18	10	14
10	15	-18	85	10	-31
11	-33	-2	25	10	-45
12	20	44	71	10	60
13	53	16	***	34	2
14	-13	-19	-41	-21	2
15	-22	-15	10	-21	106
16	46	-5	-53	-37	83
17	4	-55	-48	-6	-25
18	-3	11	3	-21	14
19	63	21	125	42	-18
20	9	11	-4	26	-9

Table A5: Individual Subject Differences for the **PFPS Group** Presented as the Percentage Difference from the Average of the Asymptomatic Group.

var/ sub #	$\Delta\rho_{max}$ [%]	$\Delta\gamma_{max}$ [%]	$PFJCF_{max}$ [%]	Q-ang [%]	weekly [%]
1	50	89	11	18	14
2	-11	-11	24	10	14
3	5	32	36	89	-20
4	-11	6	11	26	-17
5	***	36	1	26	-31
6	-31	19	-10	-6	-77
7	32	-25	-28	18	-45
8	-5	28	45	50	-59
9	89	46	-54	18	37
10	-20	-35	-10	10	-43
11	-17	16	16	-21	10
12	52	49	8	18	-63
13	46	61	23	34	-43
14	-47	-36	-78	18	-43
15	-49	-35	-27	18	37
16	-15	4	5	-21	-9
17	***	-38	16	2	-31
18	-38	55	32	-44	-31
19	95	***	***	10	-63
20	-39	42	-4	26	14

Table A6: Individual Subject Differences for the **Past-PFPS Group** Presented as the Percentage Difference from the Average of the Asymptomatic Group.

var/ sub #	$\Delta\rho_{max}$ [%]	$\Delta\psi_{max}$ [%]	F_{PFmax} [%]	Q-ang [%]	weekly [%]
1	77	18	19	-13	71
2	56	18	71	-37	-31
3	-11	48	84	-61	14
4	-32	-2	4	-53	-54
5	-68	61	-37	97	-43
6	5	52	-45	-29	-9
7	***	-46	-25	2.4	-31
8	11	-7	3	50	-54
9	-16	-46	-36	18	-31
10	-18	95	-50	10	3
11	-57	-44	-50	2	37
12	19	9	-24	10	46
13	***	***	***	26	-43
14	-18	2	-38	-21	60
15	-62	24	-45	42	-66

```
REM - **************** program: PFPS.bas*******************************
REM-----------------------------------------------------------------------
REM - written by: Pro Stergiou
REM - date      : final revisions October 30, 1995
REM - for       : Master's Thesis, University of Calgary
REM-----------------------------------------------------------------------
REM- This program will take as inputs: moments at the ankle, moments at the
REM- knee, relative position of the tibia wrt the femur, muscle PCA's,
REM- moment arm lengths and output a patellofemoral joint contact force.
REM*******************************************************************
REM- VARIBLES USED
REM
REM     ma=moment at the ankle
REM     mk=moment at the knee
REM     knang=knee angle(in degrees)
REM     knangr=knee angle(in radians)
REM     pcasol=physiological x-sectional area of the soleus
REM     pcagas=PCA of gastrocnemius
REM     pcapln=PCA of plantaris
REM     dach=moment arm length of the achilles
REM     dpat=moment arm length of the patellar ligament
REM     dgas=moment arm length of the gastrocnemius at the knee joint
REM     sach=stress of the achilles tendon
REM     fgast=force produced by the gastrocnemius muscle
REM     fpt=force of the patellar ligament
REM     fqd=force of the quadriceps tendon
REM     fptfql=ratio of patellar ligament force to quad force
REM     fpfjy=force on the PFJ along the axis of the femur
REM     fpfjx=force on the PFJ orthoganol to the axis of the femur
REM     fpfj=force in the patellofemoral joint
REM     sigma=angle of the quad tendon wrt femoral axis
REM     beta=angle of patellar ligament wrt femoral axis
REM     theta=angle of the PFJ force wrt femoral axis
REM     fmax=the maximal patellofemoral joint contact force for stance
REM     mass=mass of the subject in question
REM     timemax=time of maximal PFJ force
REM     timeimp=varible used in calculation of impulse
REM     s=varible used to integrate pfj force curve
REM     snew=variable used to calculate impulse for pfj force curve
REM     foot$=input string for which foot is being used
REM*******************************************************************
REM
REM     *************Dimensioning the variables****************
REM
```

```
DIM time(150), ma(150), mk(150), knang(150), sach(150), fgast(150), fpt(150)
DIM fqd(150), fpfjy(150), fpfjx(150), fpfj(150), fptfqd(150)
DIM sigma(150), sigmar(150), beta(150), betar(150), theta(150), thetar(150)
DIM knangr(150), dpat(150), s(150)
REM
REM     *************Reading the input data****************
REM
INPUT "What is the input filename"; filein$
PRINT
INPUT "What in the output filename"; fileout$
PRINT
OPEN filein$ FOR INPUT AS #1
OPEN fileout$ FOR OUTPUT AS #2
PRINT
PRINT
PRINT
PRINT
INPUT "What is the mass of this subject in kg"; mass
PRINT
PRINT
INPUT "Which foot is being used (r / l)"; foot$
PRINT
PRINT
PRINT "..........CALCULATIONS IN PROGRESS......PLEASE WAIT.........."
dat = 101
FOR i = 1 TO dat
      INPUT #1, time(i), ma(i), mk(i), knang(i)
NEXT i
CLOSE #1
REM*****************************************************************
REM
REM    *******Changing the data to proper positve/negative values*******
REM
FOR i = 1 TO dat
      IF foot$ = "r" THEN
            knang(i) = -1 * knang(i)
            ma(i) = -1 * ma(i)
      ELSEIF foot$ = "l" THEN
            mk(i) = -1 * mk(i)
      END IF
NEXT i
REM*****************************************************************
REM
REM     ************Entering the pre-determined PCA values*************
```

```
REM
pcasol = .00625
pcagas = .00298
pcapln = .00012
dach = .05
dgas = .015
REM*****************************************************************
REM     *************Calculating moment arm lengths***********************
REM
REM - moment arm length of the patellar tendon (ligamnent) is calculated
REM   as a function of knee angle
REM
FOR i = 1 TO dat
      IF knang(i) < 40 THEN
            dpat(i) = .00035 * knang(i) + .04
      ELSE
            dpat(i) = -.000025 * knang(i) + .051
      END IF
NEXT i
REM*****************************************************************
REM
REM     ***********************Ankle Model***************************
REM
REM - claculation of force exerted in the gastrocnemius muscle as a function
REM   of ankle moment, PCA and moment arm lengths (only applicable if
REM   ankle moment is positive or plantarflexor)
REM
FOR i = 1 TO dat
      IF ma(i) > 0 THEN
            sach(i) = ma(i) / (pcasol * dach + pcagas * dach + pcapln * dach)
            fgast(i) = sach(i) * pcagas
      ELSEIF ma(i) <= 0 THEN
            sach(i) = 0
            fgast(i) = 0
      END IF
NEXT i
REM*****************************************************************
REM
REM     ***********************Knee Model***************************
REM
REM - calculation of the patellofemoral joint contact force
REM
fmax = 0
timemax = 0
```

```
FOR i = 1 TO dat
REM - using only knee extensor moments
      IF mk(i) <= 0 THEN
            mk(i) = 0
      ELSEIF mk(i) > 0 THEN
            fpt(i) = (mk(i) - (fgast(i) * dgas)) / dpat(i)
      END IF
      IF fpt(i) < 0 THEN
            fpt(i) = 0
      END IF
      fptfqd(i) = -.01 * knang(i) + 1.2
      fqd(i) = fpt(i) / fptfqd(i)
      sigma(i) = -(knang(i) / 10) + 8
      beta(i) = 160 - (.617 * knang(i)) - 3
      sigmar(i) = (3.14 * sigma(i)) / 180
      betar(i) = (3.14 * beta(i)) / 180
      fpfjy(i) = fqd(i) * COS(sigmar(i)) + fpt(i) * COS(betar(i) - 1.57)
      fpfjx(i) = fqd(i) * SIN(sigmar(i)) + fpt(i) * COS(betar(i) - 1.57)
      fpfj(i) = SQR(fpfjy(i) ^ 2 + fpfjx(i) ^ 2) / mass
      IF fpfjy(i) > 0 THEN
            thetar(i) = ATN(fpfjx(i) / fpfjy(i))
            theta(i) = (thetar(i) * 180) / 3.14
      ELSEIF fpfjy(i) = 0 THEN
            theta(i) = 0
      END IF
REM - finding the maximal patellofemoral joint compressive force and time
      IF fpfj(i) > fmax THEN
            fmax = fpfj(i)
            timemax = i
      END IF
      PRINT #2, fpfj(i), theta(i)
NEXT i
REM*********************************************************************
REM
REM     *******Integration of the PFJ Force Curve**************************
REM
snew = 0
FOR i = 2 TO dat - 1
      s(i) = fpfj(i) + fpfj(dat)
      snew = s(i) + snew
NEXT i
i = 1
timeimp = 1
impulse = timeimp / 2 * (fpfj(i) + 2 * (snew))
```

```
PRINT #2,
PRINT #2, "The maximal PFJ force is"; fmax; "N/kg at"; timemax; "% of stance"
PRINT #2,
PRINT #2, "The impulse is"; impulse; "N/kg . % stance"
CLOSE #2
PRINT "PFJ force is"; fmax
PRINT "Impulse is"; impulse
PRINT "The time is"; timemax
END
```

```
%************ Transformation Measurements Program **********************
%
%-----------------------------------------------------------------
% original: Asra Kahn
% revised:  Pro Stergiou
% date: (final version) November, 1994
%-----------------------------------------------------------------

% matlab function file
% to calculate the marker positions in the joint co-ord system from kintrak *.ted files
   manipulated
% in EV by 'list/re' command
% input to this program is the: 1).asc file, 2)segment lengths.

% set up input and output files and names
filename = input('please enter the name of the data file (keep suffix) ' , 's')
outfile = input('please enter name of the output file ' , 's')
disp(' ok, reading in data')

% remove all numerical data from input file and write marker names to file
markernamer.asc
eval(['!grep Object ' filename '| sed s/.............// > markernames.asc'])

% remove non-numerical data from the input file and write data to matrix file
temp.asc
eval(['!grep .0 ' filename ' > temp.asc '])

% open marker name file and *.meas file
fid2 = fopen( outfile , 'a');
fid3 = fopen( 'markernames.asc' , 'r');

% read in marker data from file temp.* to matrix temp
load temp.asc;

% since down must be positive in the transformation co-ord system multiply vert
co-ord by -1.
temp(:,6) = -1*temp(:,6);
temp(:,5) = -1*temp(:,5);
!rm temp.asc

% calculation of the total number of markers
nummarkers =  max(temp(:,1));
```

```
% calculation of the total number of frames
totalframes = max(temp(:,2)) - min(temp(:,2)) +1;

% input segment lenghts
footlength = input('what is length of foot in cm from floor? ')
leglength = input('what is length of lower leg in cm ')
thighlength = input('what is length of thigh in cm ')


% enter marker data in marker matrices
for n = 1:nummarkers
        dummy = fscanf(fid3, '%s19',1);
        eval([ dummy '(:,[2 3 1]) = temp((n-1)*totalframes+1 : n*totalframes ,
  4:6);'])
        %eval(['M' int2str(n) ' = dummy ;' ])
end

% defining the joint centres


%ankle joint centre
ankle(:,1) = lat_ankle(:,1);
ankle(:,2) = lat_ankle(:,2);
ankle(:,3) = ant_ankle(:,3);

%knee joint centre
knee(:,1) = lat_knee(:,1);
knee(:,2) = lat_knee(:,2);
knee(:,3) = ant_knee(:,3);

%hip joint centre
hip(:,1) = lat_hip(:,1);
hip(:,2) = lat_hip(:,2);
hip(:,3) = ant_hip(:,3);

%calculate new marker co-ordinates.

%foot
lat_foot = mean(lat_foot - ankle)
low_calc = mean(low_calc - ankle)
up_calc = mean(up_calc - ankle)

%lower leg
low_leg = mean(low_leg - knee)
```

```
mid_leg = mean(mid_leg - knee)
up_leg = mean(up_leg - knee)

%upper leg
low_thigh = mean(low_thigh - hip)
mid_thigh = mean(mid_thigh - hip)
up_thigh = mean(up_thigh - hip)

%print data out to trial.meas
fprintf(fid2, 'lat_foot \n %6.2f  %6.2f  %6.2f  %6.2f \n\n' , lat_foot, footlength);
fprintf(fid2, 'low_calc \n %6.2f  %6.2f  %6.2f  %6.2f \n\n' , low_calc, footlength);
fprintf(fid2, 'up_calc \n %6.2f  %6.2f  %6.2f  %6.2f \n\n' , up_calc, footlength);
fprintf(fid2, 'low_leg \n %6.2f  %6.2f  %6.2f  %6.2f \n\n' , low_leg, leglength);
fprintf(fid2, 'mid_leg \n %6.2f  %6.2f  %6.2f  %6.2f \n\n' , mid_leg, leglength);
fprintf(fid2, 'up_leg \n %6.2f  %6.2f  %6.2f  %6.2f \n\n', up_leg, leglength);
fprintf(fid2, 'low_thigh \n %6.2f  %6.2f  %6.2f  %6.2f \n\n' , low_thigh,
thighlength);
fprintf(fid2, 'mid_thigh \n %6.2f  %6.2f  %6.2f  %6.2f \n\n' , mid_thigh,
thighlength);
fprintf(fid2, 'up_thigh \n %6.2f  %6.2f  %6.2f  %6.2f \n\n' , up_thigh, thighlength);


%%clean up
!rm markernames.asc
status = fclose(fid2)

fprintf(1,'all done!')
```